The K^0_L Facility at

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Moskov Amaryan

Old Dominion University

7th Workshop of the APS Topical Group on Hadronic Physics, January 3, 2017, Washington DC

A Letter of Intent to Jefferson Lab PAC-43.

Physics Opportunities with a Secondary K_L^0 Beam at JLab.

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(Dated: May 15, 2015)

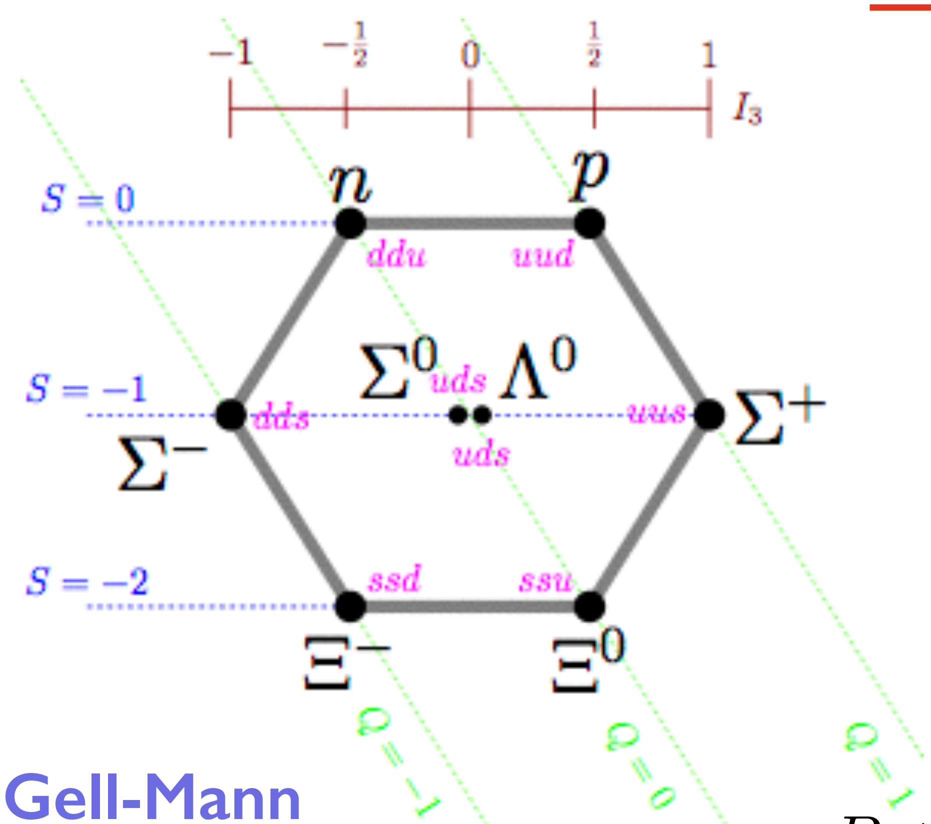
Outline

- Introduction
- Baryon Multiplets
- Reactions with K^0_L beam on proton target
- Experimental Arrangement
- K^0_L Beam at GlueX
- Expected rates
- Summary

Constituent Quark Model

SU(3)

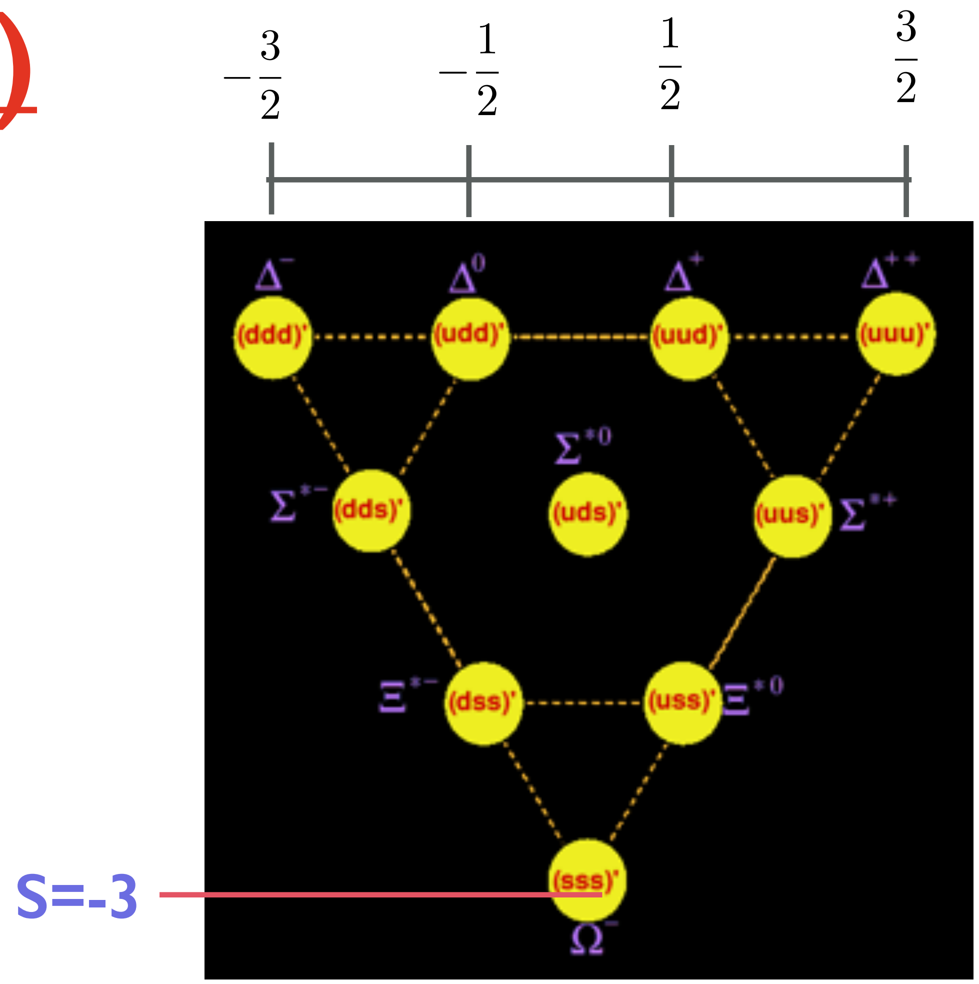
Octet



Gell-Mann Nishidjima

$$Q = I_3 + \frac{B+S}{2}$$

Decuplet

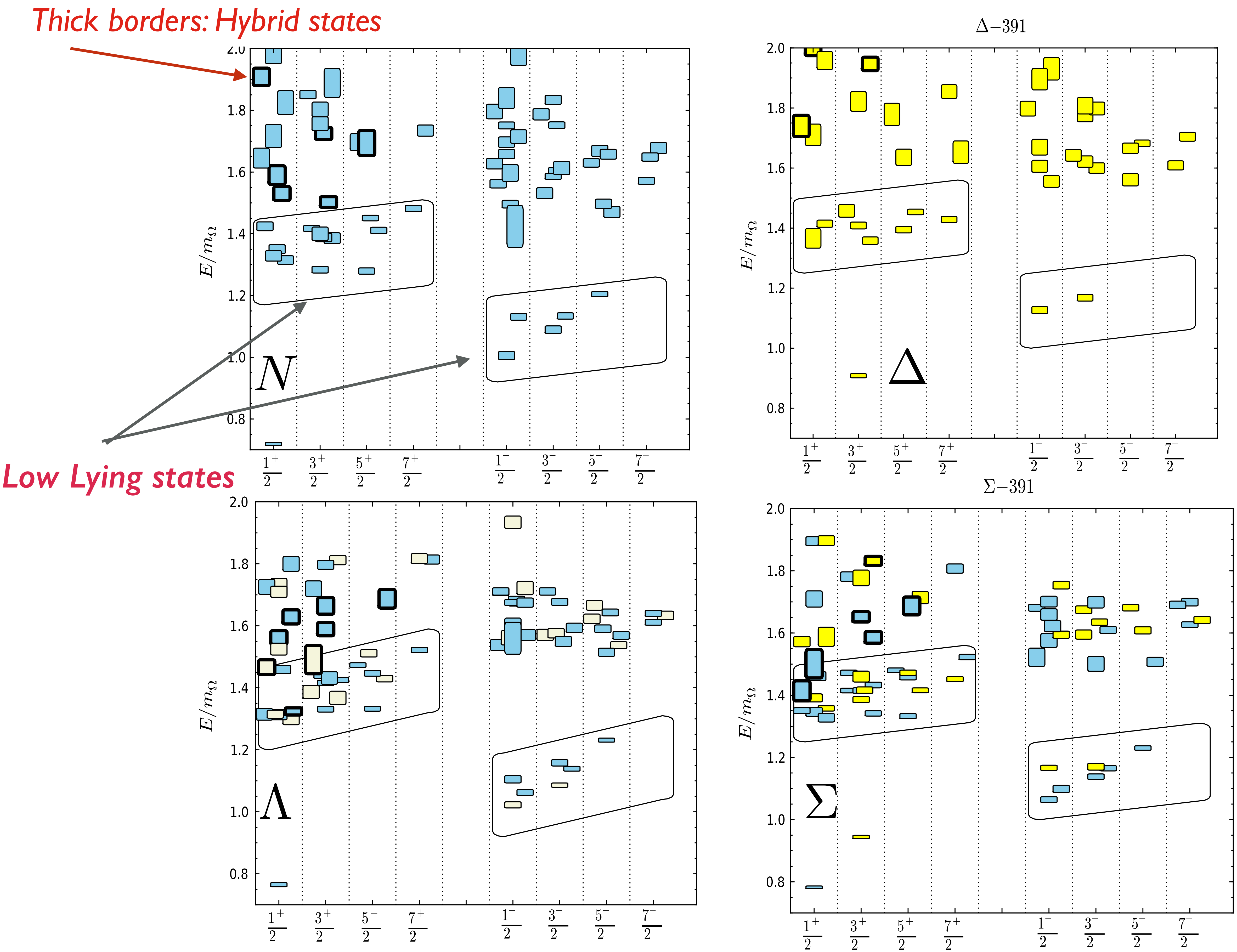


But there are many more states predicted, where are they?

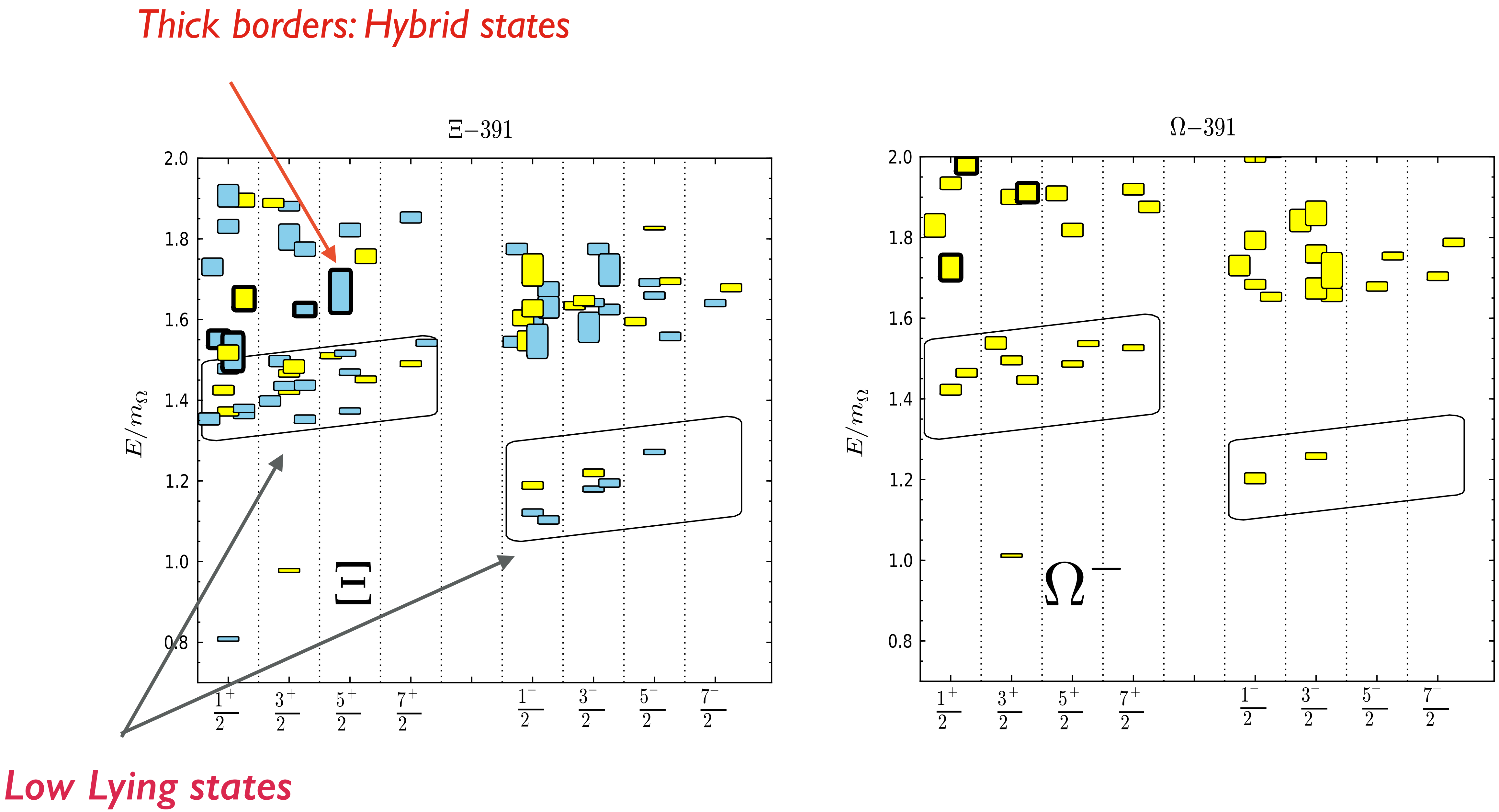
Where are hybrids, glueballs, multiquark states ?

Did we already observe some of them?

Lattice QCD calculations

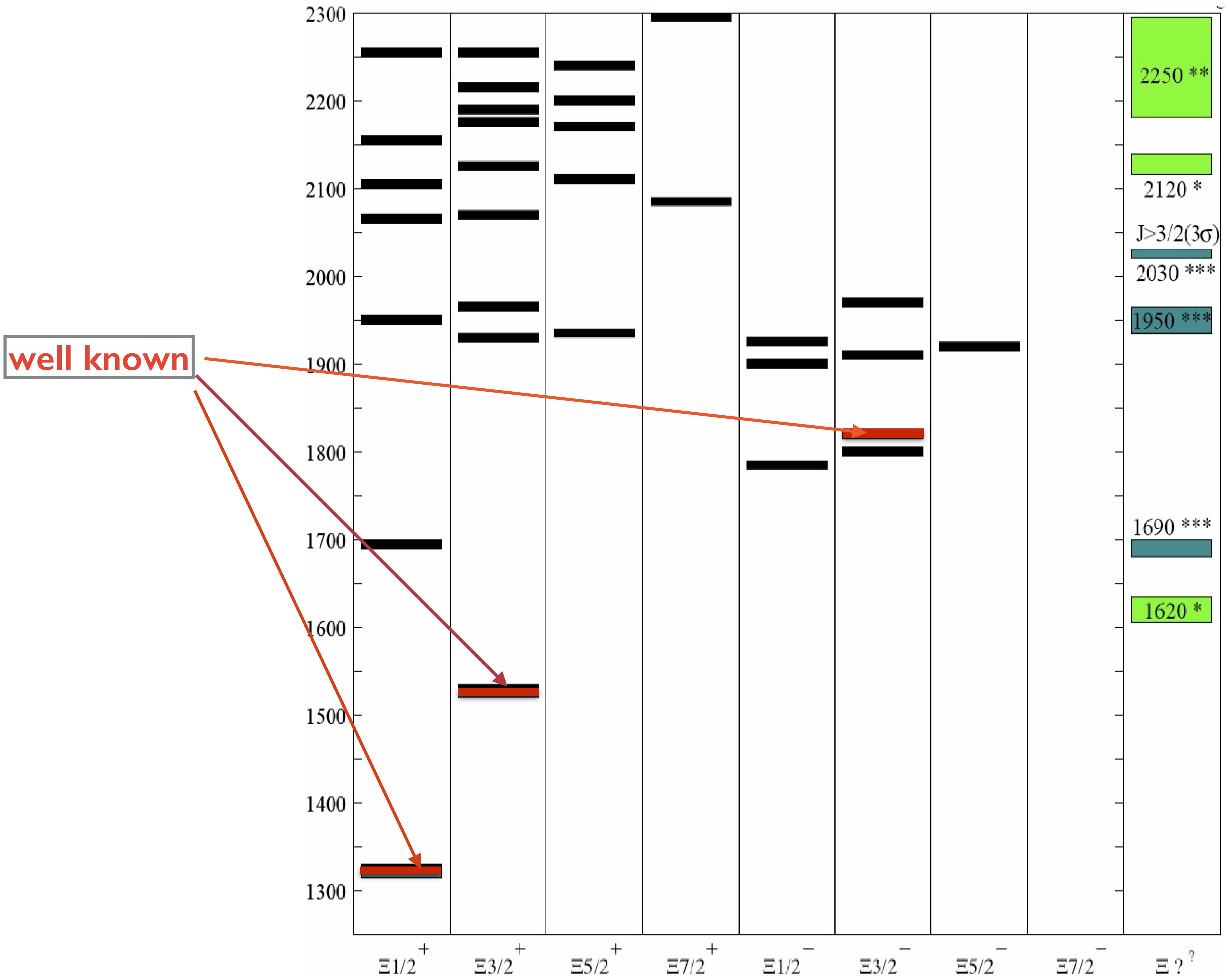


Lattice QCD calculations



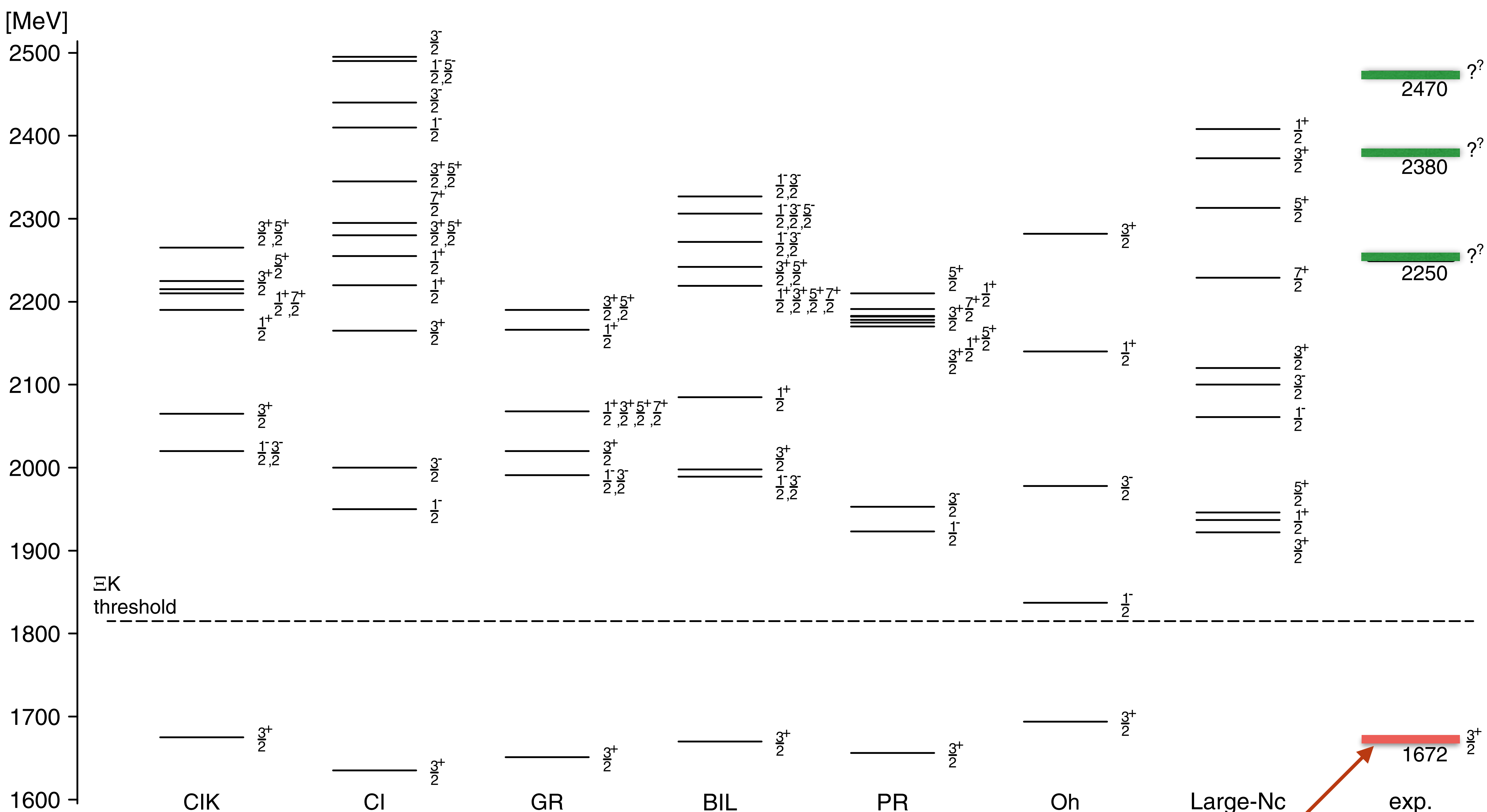
Edwards, Mathur, Richards and Wallace
Phys. Rev. D 87, 054506 (2013)

Status of Ξ*



well known
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
2250 **
2120 *
J>3/2(3σ)
2030 ***
1950 ***
1690 ***
1620 *
Ξ1/2+
Ξ3/2+
Ξ5/2+
Ξ7/2+
Ξ1/2−
Ξ3/2−
Ξ5/2−
Ξ7/2−
Ξ ??

Status of Ω^{-*}



only one well known state?

- **Three light quarks** can be arranged in **6** baryonic families, N^*, Δ^*, Λ^*, Σ^*, Ξ^*, & Ω^*.
- **Number of members** in a family that can exist **is not arbitrary**.
- If **$SU(3)_F$** symmetry of **QCD** is controlling, then:

Octet: N^*, Λ^*, Σ^*, Ξ^*
Decuplet: Δ^*, Σ^*, Ξ^*, & Ω^*

  - Number of experimentally identified resonances of each baryon family in PDG summary tables is **17** N^*, **24** Δ^*, **14** Λ^*, **12** Σ^*, **7** Ξ^*, & **2** Ω^*.
  - **Constituent Quark** models, for instance, predict existence of no less than **64** N^*, **22** Δ^* states with **mass < 3** GeV.

- Seriousness of "**missing-states**" problem is obvious from these numbers.

- To complete **$SU(3)_F$** multiplets, one needs no less than **17** Λ^*, **41** Σ^*, **41** Ξ^*, & **24** Ω^*.

Recourse to the Neutral Kaon System

Strangeness eigenstates with $J^{PC} = 0^{-+}$

$$|K^0\rangle = |d\bar{s}|, \qquad |\bar{K}^0\rangle = |\bar{d}s|$$

S=+1 **S=-1**

Parity *eigenstates with intrinsic* $P = -1$

$$P|K^0\rangle = -|K^0\rangle, \qquad P|\bar{K}^0\rangle = -|\bar{K}^0\rangle$$

Effect of ***C-Parity*** *can be taken to be*

$$C|K^0\rangle = |\bar{K}^0\rangle, \qquad C|\bar{K}^0\rangle = |K^0\rangle$$

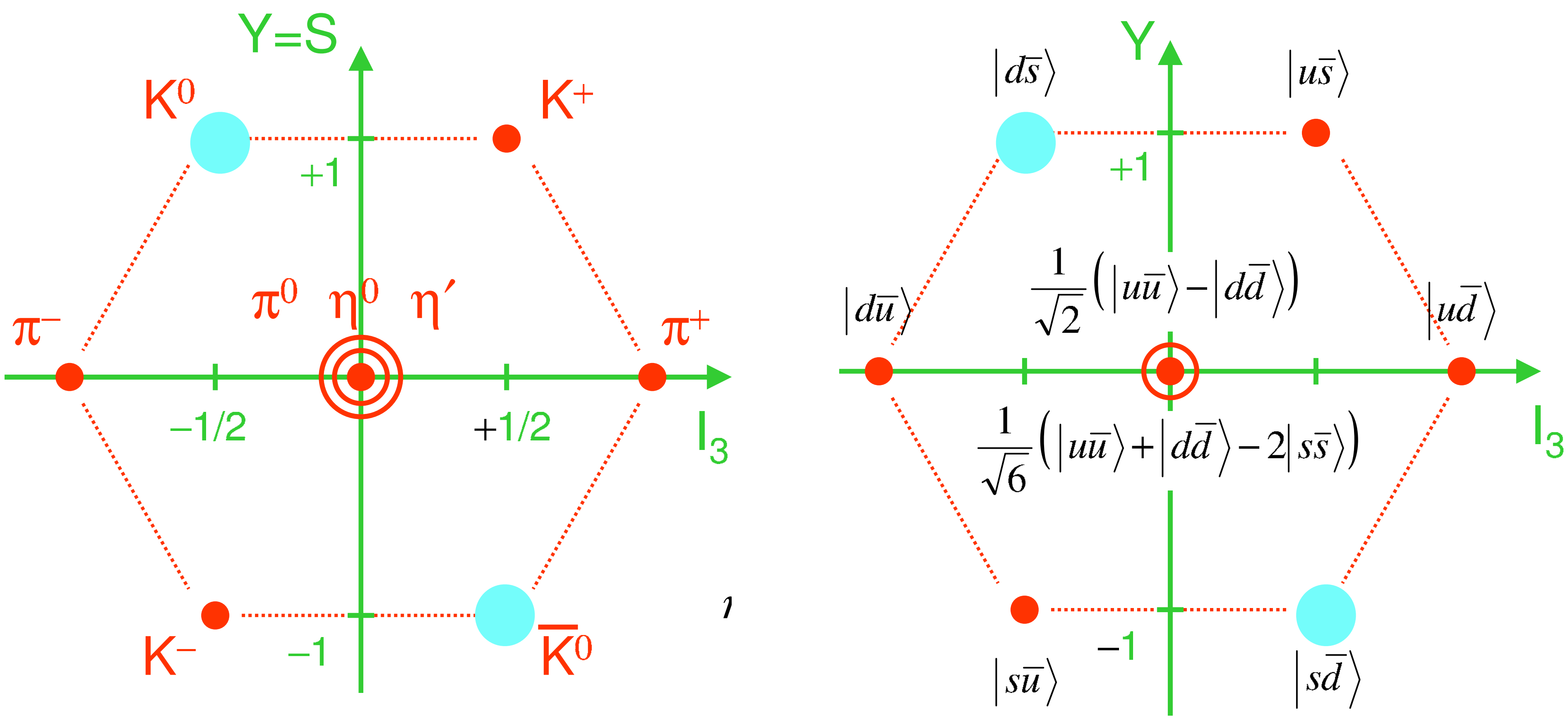
However not ***CP*** *eigenstates*

$$CP|K^0\rangle = -|\bar{K}^0\rangle, \qquad CP|\bar{K}^0\rangle = -|K^0\rangle$$

CP eigenstates can be formed

$$|K_1\rangle \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right) ; \qquad CP\,|K_1\rangle = +\,|K_1\rangle$$

$$|K_2\rangle \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}^0\rangle\right) ; \qquad CP\,|K_2\rangle = -\,|K_2\rangle$$



$$K^0 \quad and \quad \bar{K}^0$$

are unstabile particles decaying via WI

$$K_S(K - short) \quad and \quad K_L(K - long)$$

propagate as free particles and have distinct lifetimes

$$\tau_S = 0.9 \times 10^{-10} s \quad and \quad \tau_L = 0.5 \times 10^{-7} s \ (c\tau = 15\ m)$$

$$|K_S\rangle \equiv \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_1\rangle + \epsilon|K_2\rangle) \approx |K_1\rangle$$

$$|K_L\rangle \equiv \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle) \approx |K_2\rangle$$

$|\epsilon| \approx 2.3 \times 10^{-3}$ ***defines the level of CP violation***

CP conserving decays

$$\mathrm{K_S} \to \pi^+\pi^- \qquad \mathrm{BR} = 68.6\%$$
$$\to \pi^0\pi^0 \qquad \mathrm{BR} = 31.4\%$$

$$\mathrm{K_L} \to \pi^+\pi^-\pi^0 \qquad \mathrm{BR} = 12.6\%$$
$$\to \pi^0\pi^0\pi^0 \qquad \mathrm{BR} = 21.1\%$$
$$\to \pi^- \mathrm{e}^+ \nu_\mathrm{e} \qquad \mathrm{BR} = 19.4\%$$
$$\to \pi^+ \mathrm{e}^- \overline{\nu}_\mathrm{e} \qquad \mathrm{BR} = 19.4\%$$
$$\to \pi^- \mu^+ \nu_\mu \qquad \mathrm{BR} = 13.6\%$$
$$\to \pi^+ \mu^- \overline{\nu}_\mu \qquad \mathrm{BR} = 13.6\%$$

CP violating decays observed in 1964

$$\mathrm{K_L} \to \pi^+\pi^- \qquad \mathrm{BR} = 2.1 \times 10^{-3}$$
$$\to \pi^0\pi^0 \qquad \mathrm{BR} = 9.4 \times 10^{-4}$$

What can be learned with a K^0_L beam ?

List of reactions:

Elastic and charge-exchange

$$K^0_L p \to K^0_S p$$
$$K^0_L p \to K^+ n$$

Two-body with S=-1

$$K^0_L p \to \pi^+ \Lambda$$
$$K^0_L p \to \pi^+ \Sigma^0$$

Two-body with S=-2

$$K^0_L p \to K^+ \Xi^0$$
$$K^0_L p \to K^+ \Xi^{0*}$$

Three-body with S=-2

$$K^0_L p \to \pi^+ K^+ \Xi^-$$
$$K^0_L p \to \pi^+ K^+ \Xi^{-*}$$

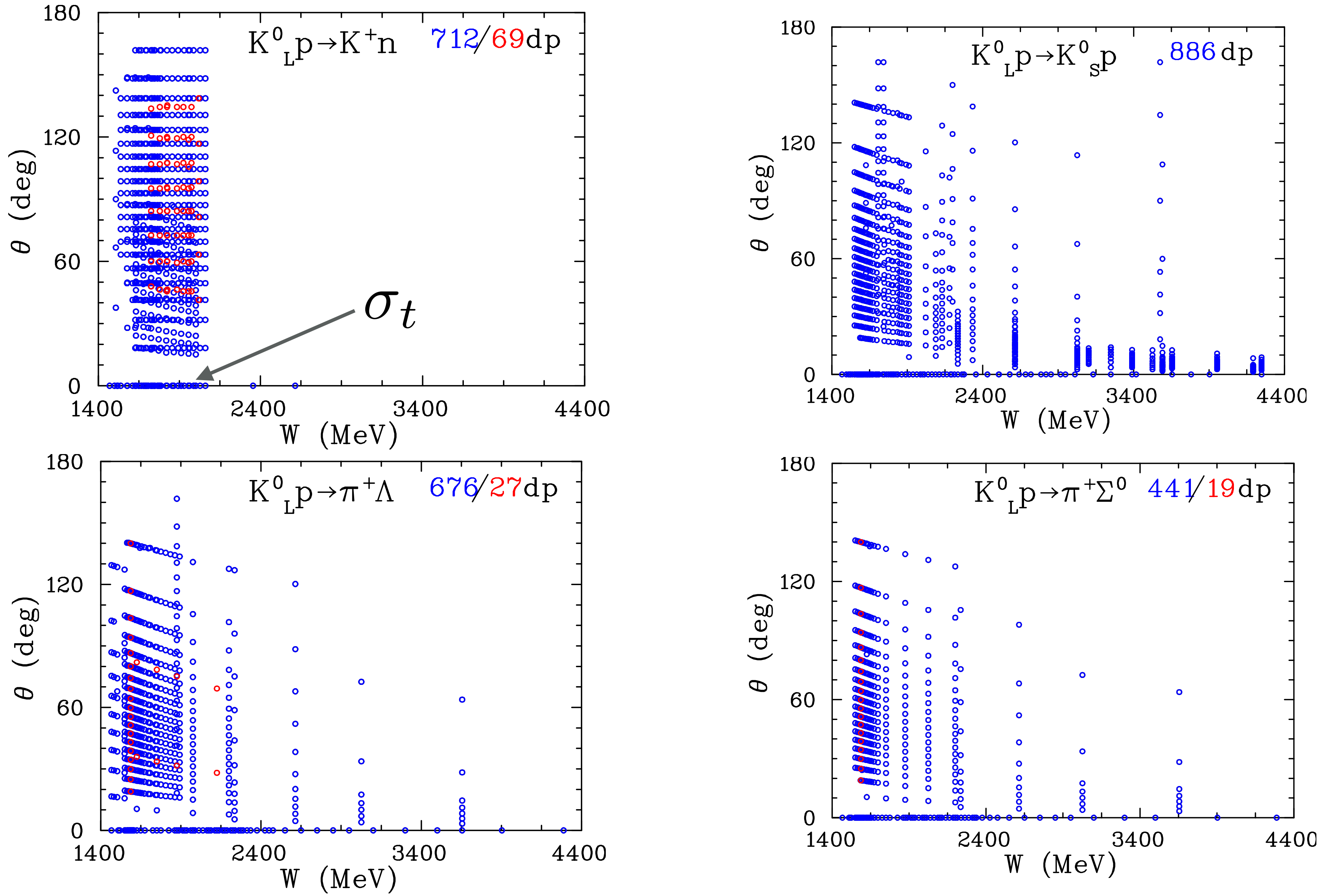
Three-body with S=-3

$$K^0_L p \to K^+ K^+ \Omega^-$$
$$K^0_L p \to K^+ K^+ \Omega^{-*}$$

Very Limited World Data with K_L beam

(Mainly low stat. bubble chamber data. Compilation by I. Strakovsky)

blue points: $d\sigma/d\Omega$ *red points: Polarization*



we are not aware of any data on Neutron target

Expected Cross Sections vs Bubble Chamber Data

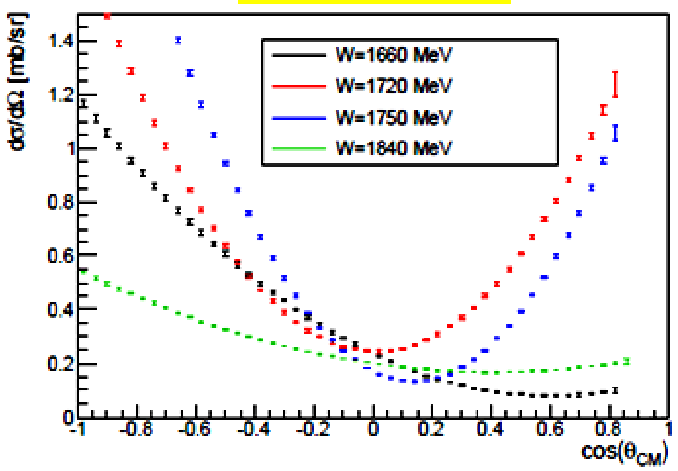
- **GlueX** measurements will span **cosθ** from **–0.95** to **0.95** in c.m. above **W** = **1490** MeV.

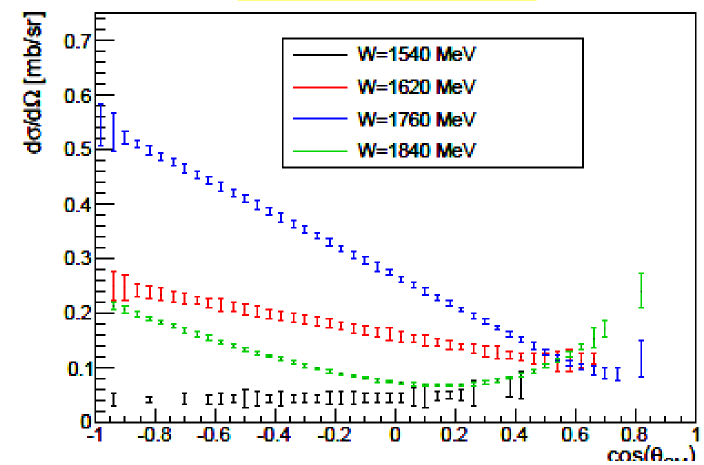
- K_L rate is **10^5** K_L/s.
- Uncertainties correspond to **100** days of running time.
- Cross section uncertainty estimates (statistics only) for

Courtesy of Simon Taylor, KL2016
Mark Manley, KL2016

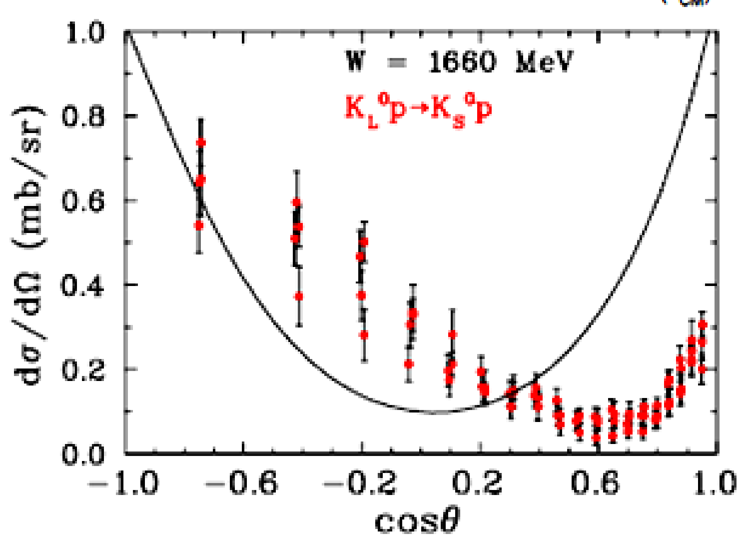
$K_Lp \to K_Sp$ | $K_Lp \to \pi^+\Lambda$

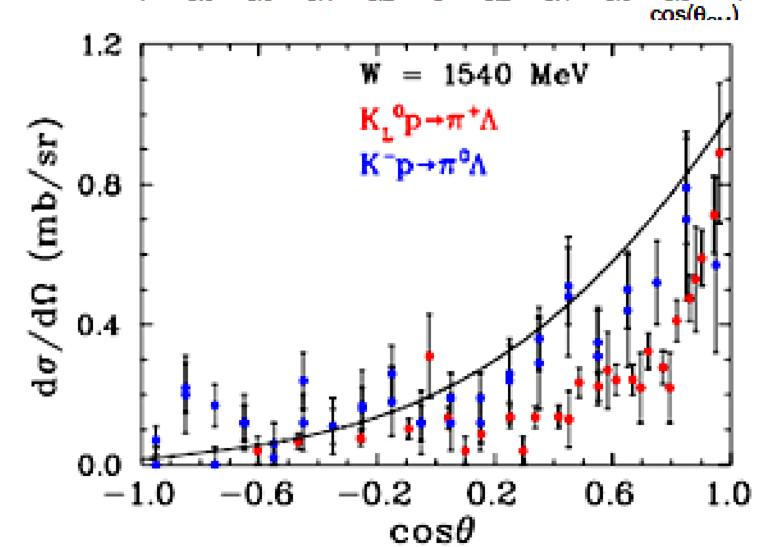
Expected **GlueX** Data





BC Data





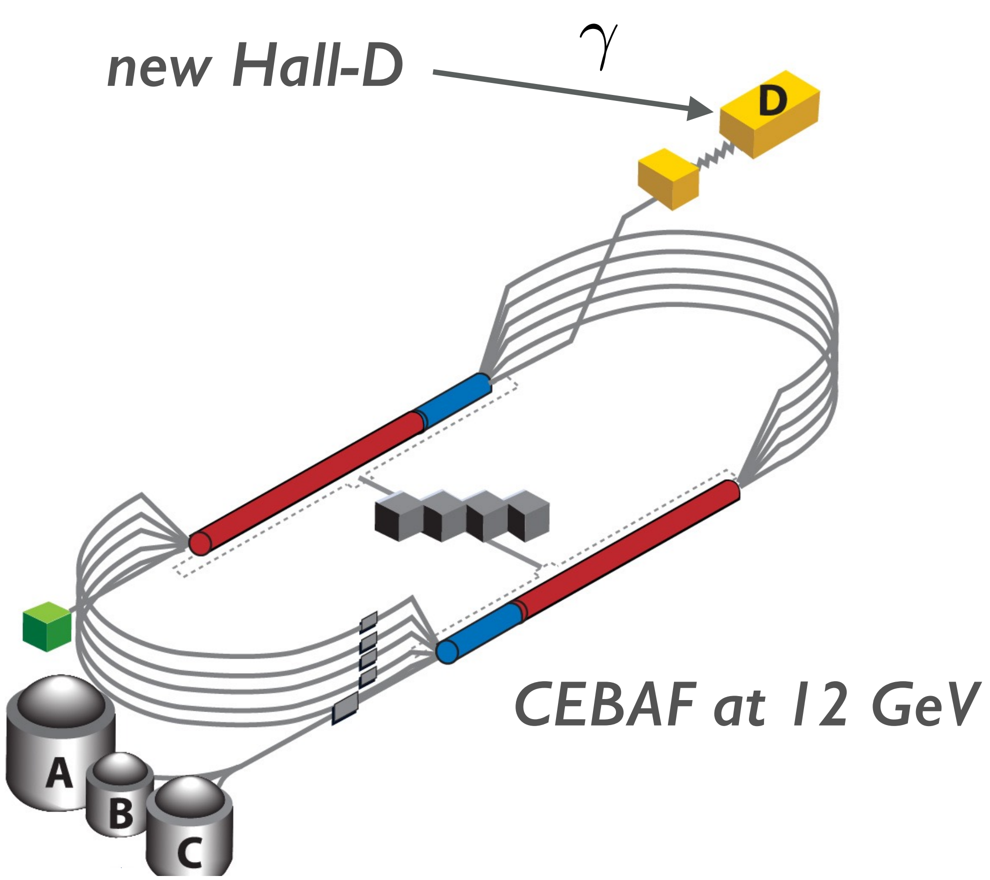
More details in KL2016 Workshop Proceedings

arXiv: 1604.02141

How to make a kaon beam?

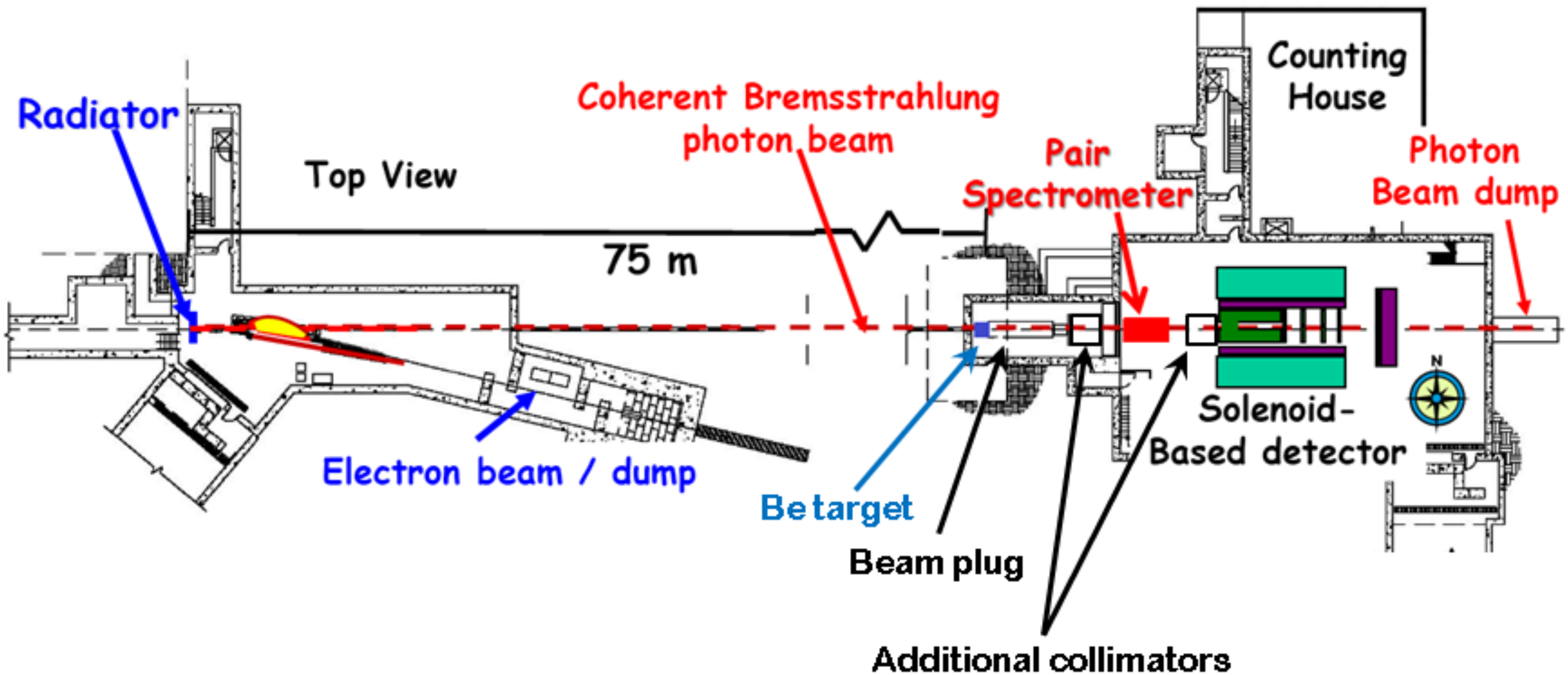
Thomas Jefferson National Accelerator Facility

Aerial View

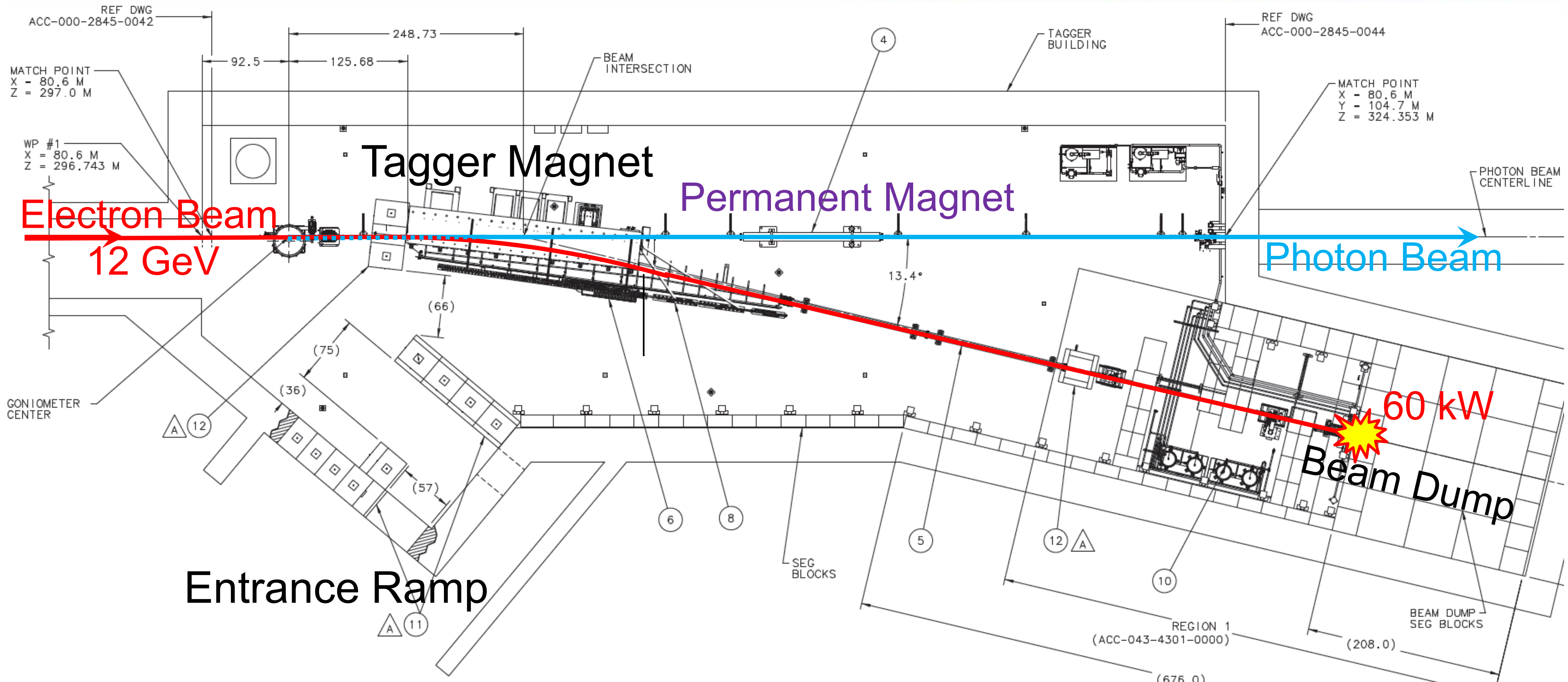


Hall D Beamline

Current setup



Hall D Tagger Area



- Design beam current limits: 5 μA (60 kW) max
- Design radiator thickness: ~0.0005 Radiation Lengths max
- Challenge: Increase radiator thickness to 0.05-0.10 R.L.?!

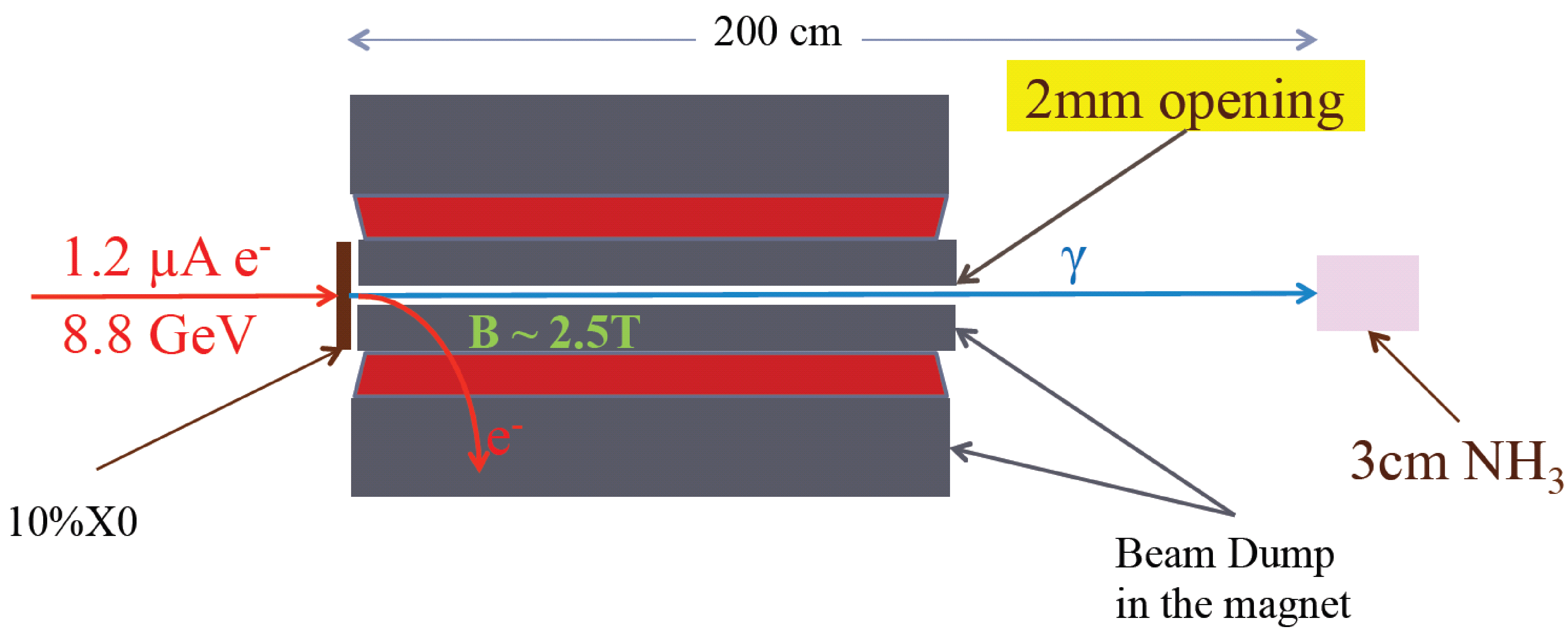
Compact Photon Source Concept

- Strong magnet after radiator deflects exiting electrons
- Long-bore collimator lets photon beam through
- Electron beam dump placed next to the collimator
- Water-cooled Copper core for better heat dissipation
- Hermetic shielding all around and close to the source
- High Z and high density material for bulk shielding
- Borated Poly outer layer for slowing, thermalizing, and absorbing fast neutrons still exiting the bulk shielding
- No need in tagging photons, so the design could be compact, as opposed to the Tagger Magnet concept

CPS: PR12-15-003 Proposal at JLab

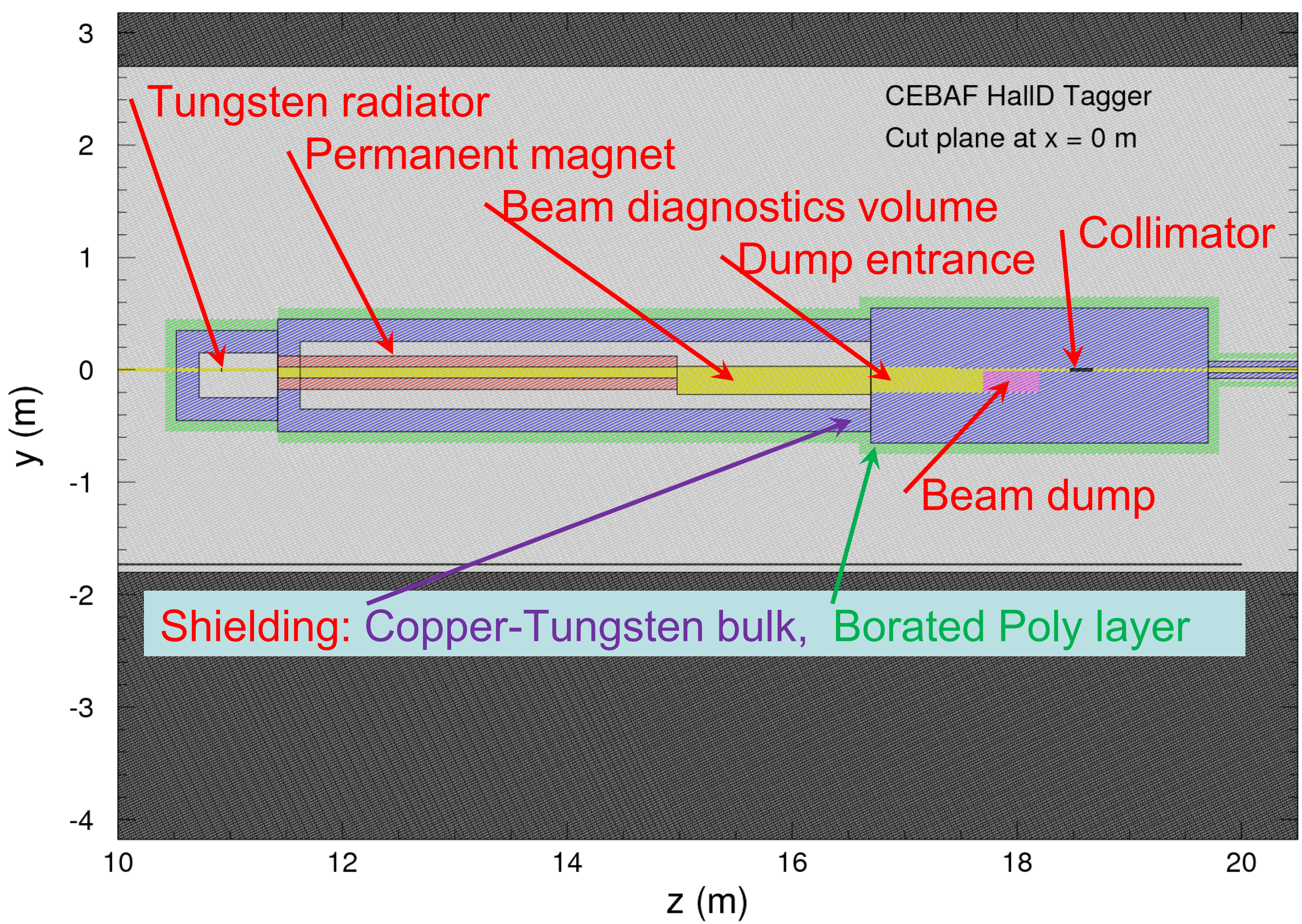
Application example: CPS concept for new experiment in Hall A

Distance to target ~200 cm
photon beam diameter on the target ~ 0.9 mm

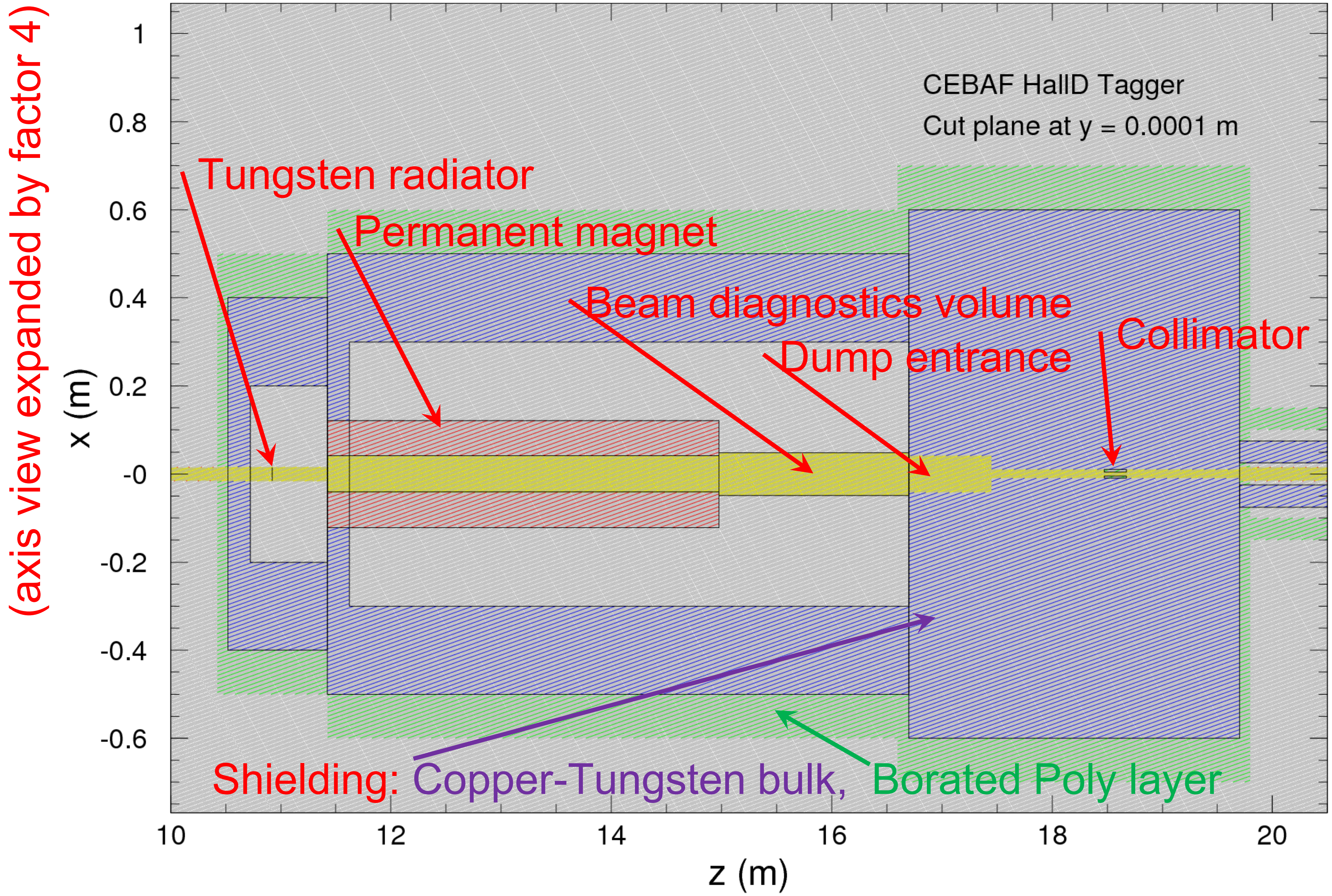


MC simulation and direct calculations show acceptable background rates on SBS and NPS.

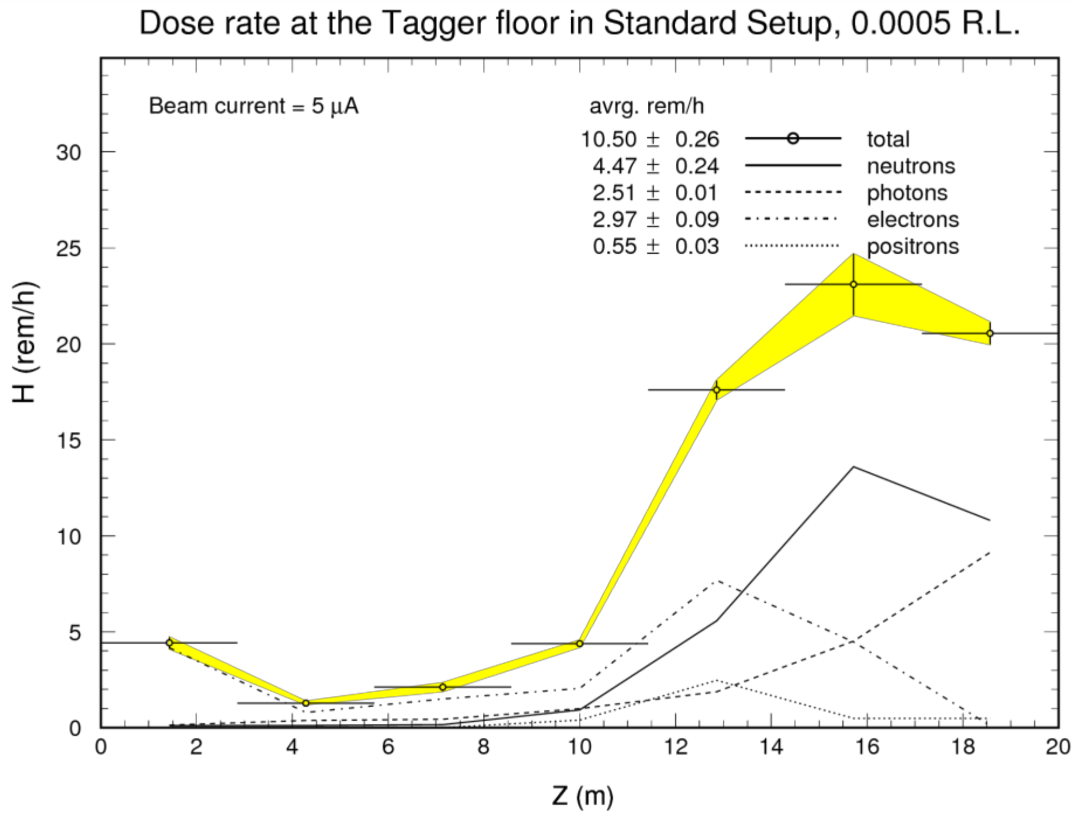
CPS at the Hall D Tagger Area

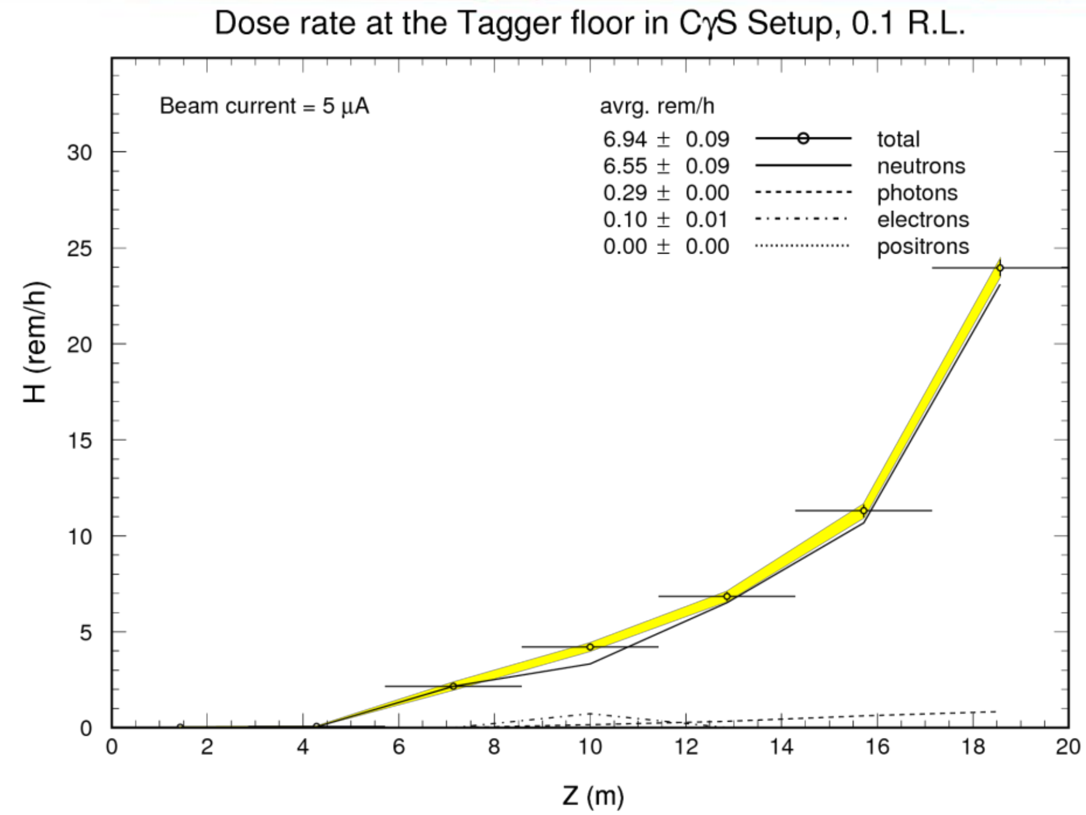


CPS, horizontal plane (1)



Dose Rate Evaluation and Comparison





- The dose rates in the Tagger vault for the CPS setup with 10% R.L. radiator are close to Standard XD ops
- The radiation spectral composition is different; most of the contribution in the CPS setup is from higher energy neutrons

Dose Rate Evaluation and Comparison

- The plots show comparison of dose rate estimates in the Tagger Area in two conditions: (1) nominal Hall D operation with the standard amorphous radiator at 0.0005 R.L., - with (2) radiator at 0.1 R.L., used as part of the Compact Photon Source setup.
- The comparison indicates that at equal beam currents, gamma radiation dose rates are much smaller for the CPS run (~order of magnitude), and neutron dose rates in the area are comparable.
- Design and shielding optimization may improve the comparison further in favor of the CPS solution

More discussions on CPS at the Workshop

„New Opportunities with High-Intensity Photon Sources“ February 6-7, 2017 at CUA

https://www.jlab.org/conferences/HIPS2017/

K^0_L beam (continued)

-Electron beam with $I_e = 5\mu A$

-Delivered with 64 ns bunch spacing avoids overlap in the range of P=0.3-10.0 GeV/c

-Momentum measured with TOF

-K^0_L flux mesured with pair spectrometer

-Side remark: Physics case with polarized targets is under study and feasible

Rate of neutrons and K^0_L on GlueX target

- **PRL22.996 (1969) Brody et al.**

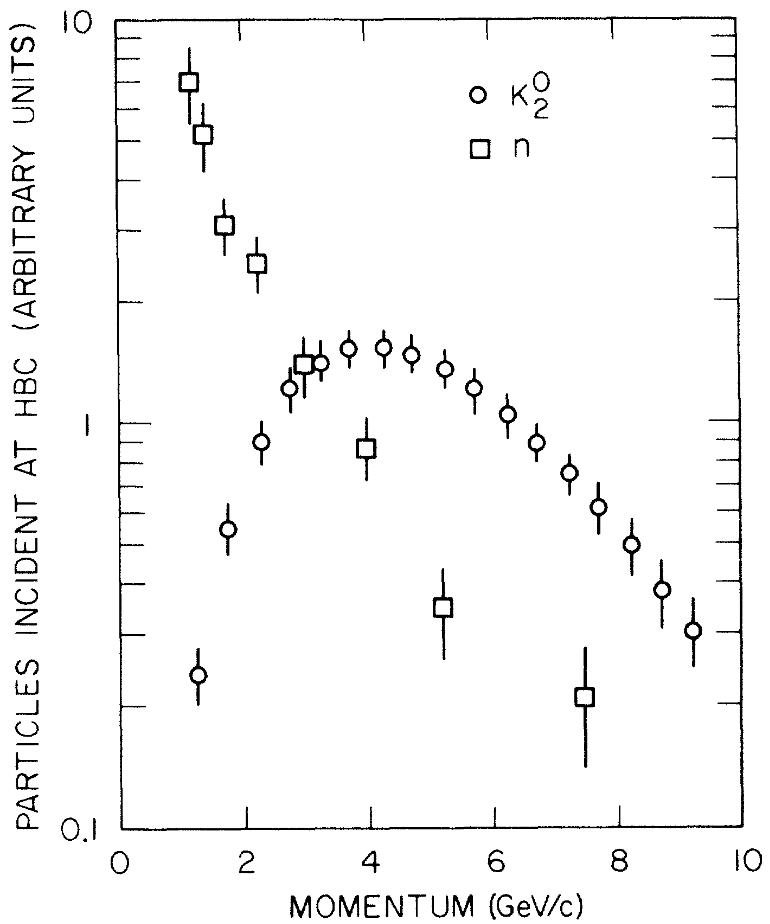
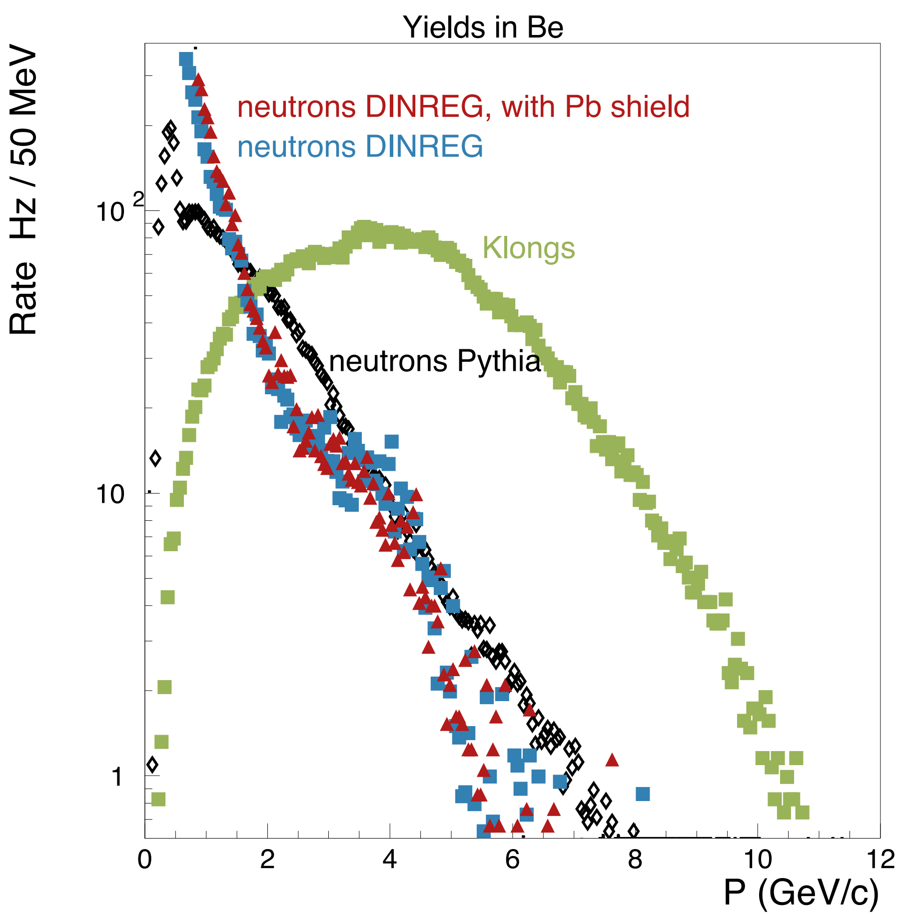


FIG. 2. Comparison of the neutron and $K_2{}^0$ fluxes at the hydrogen bubble chamber for 2° production with 16-GeV electrons.

- **JLAB**



- **With a proton beam ratio $n/K_L = 10^3$-10^4**

- **ProjectX (Fermi Lab) arXiv:1306.5009**

Table III-2: Comparison of the K_L production yield. The BNL AGS kaon and neutron yields are taken from RSVP reviews in 2004 and 2005. The *Project X* yields are for a thick target, fully simulated with LAQGSM/MARS15 into the KOPIO beam solid angle and momentum acceptance.

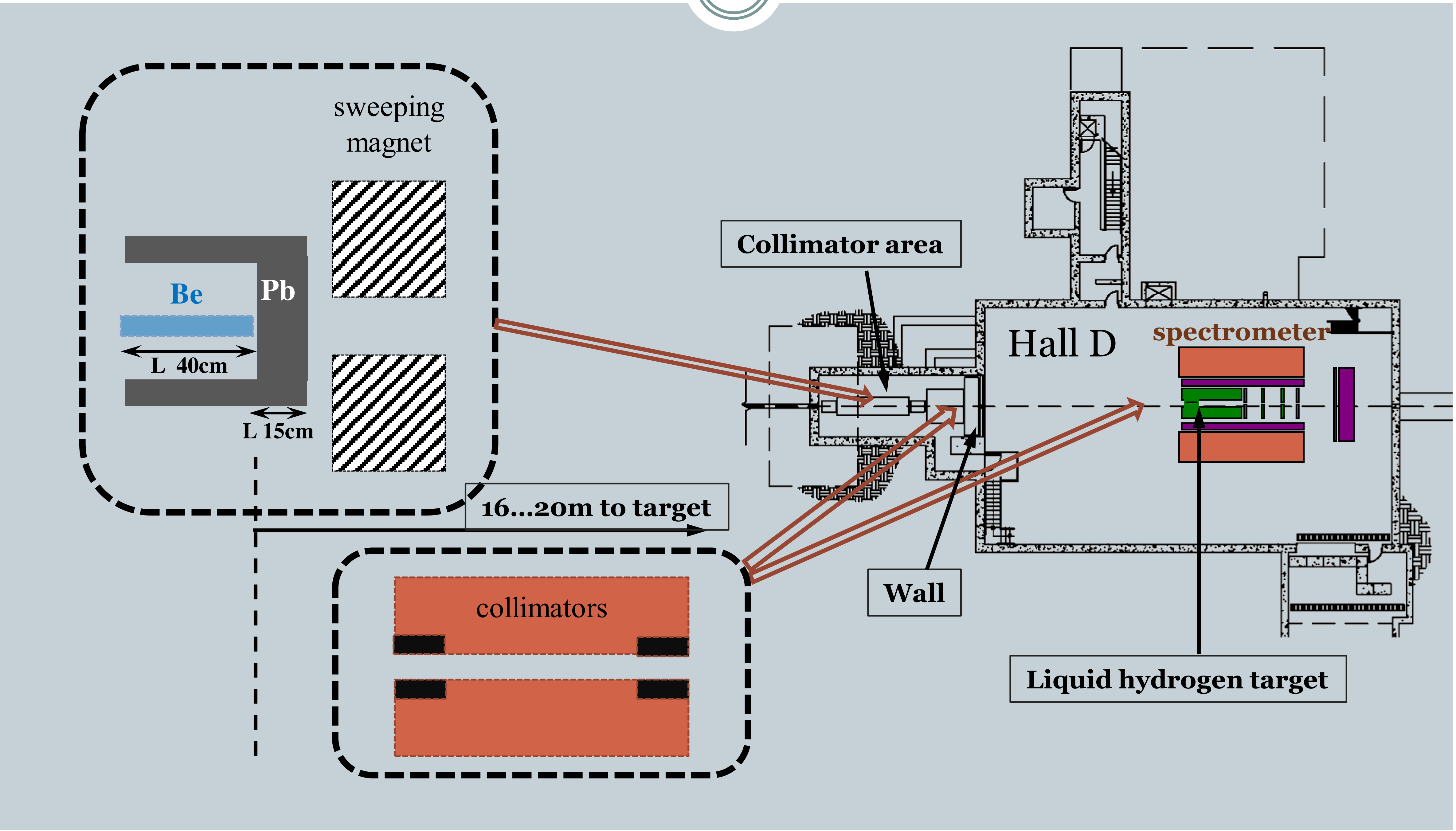
	Beam energy	Target (λ_I)	$p(K)$ (MeV/c)	K_L/s into 500 μsr	$K_L : n$ ($E_n > 10$ MeV)
BNL AGS	24 GeV	1.1 Pt	300-1200	60×10^6	$\sim 1 : 1000$
Project X	3 GeV	1.0 C	300-1200	450×10^6	$\sim 1 : 2700$

KL beam can be used to study rare decays
However it will be impossible to use it for hyperon spectroscopy because of momentum range and n/K Ratio

K^0_L beam

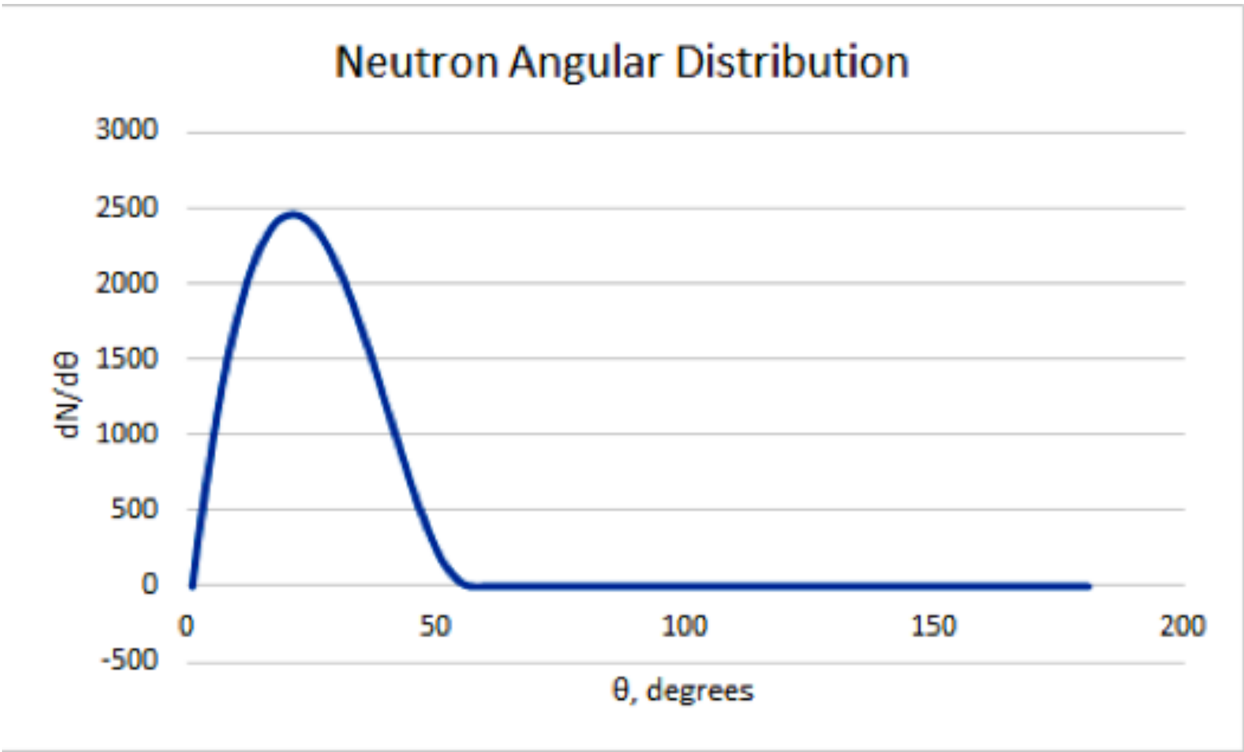
Electron beam	$E_e = 12GeV; I_e = 5\mu A$
Radiator (rad. length)	10%
Be target (R=3cm)	$L = 40cm$
LH2 target(L=30cm)	$R = 3cm$
Distance Be-LH2	16m
K_L Rate/sec	~10^4

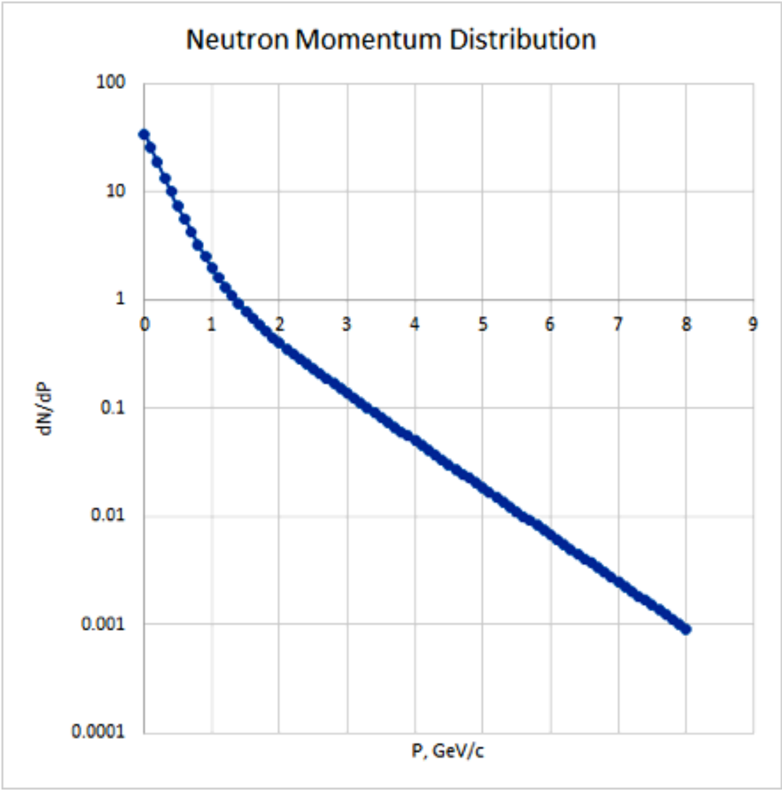
K_L-beam line

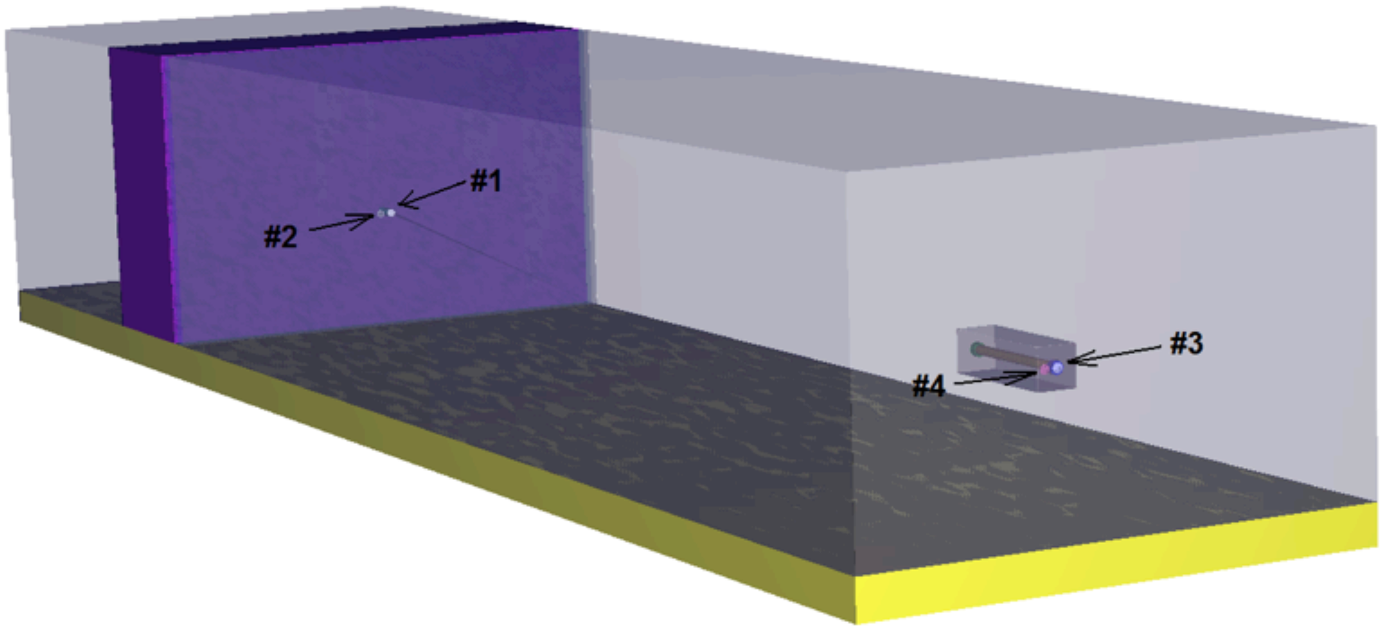

sweeping
magnet
Be
Pb
L 40cm
L 15cm
16…20m to target
collimators
Collimator area
Hall D
spectrometer
Wall
Liquid hydrogen target

Neutron Background

Neutron calculations for the KLF Project using MCMP6



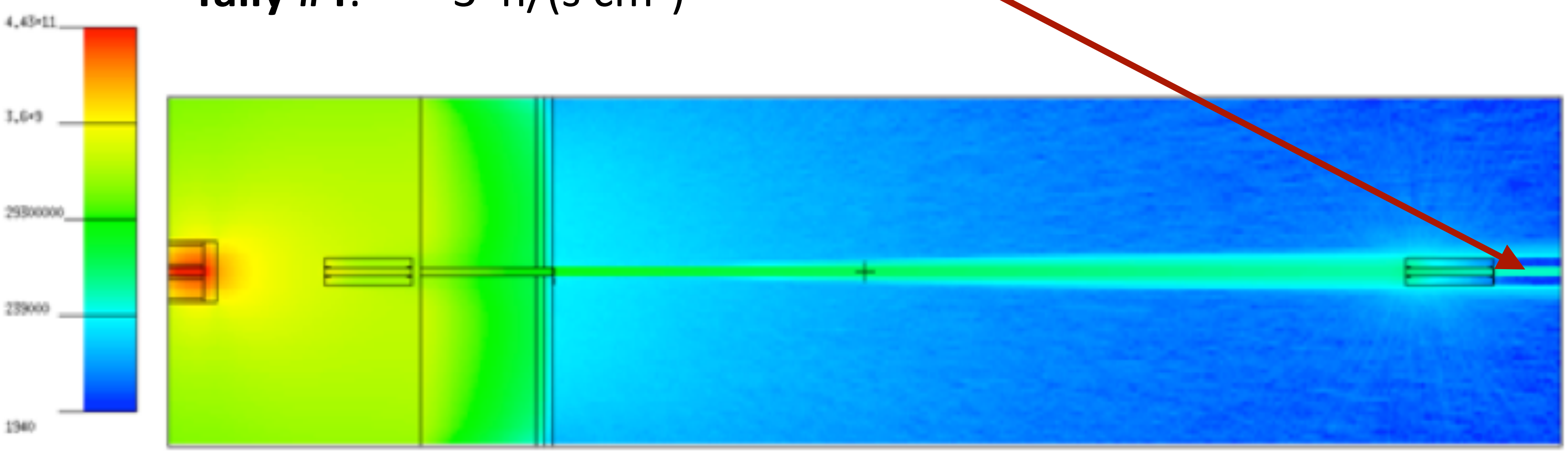




Results:

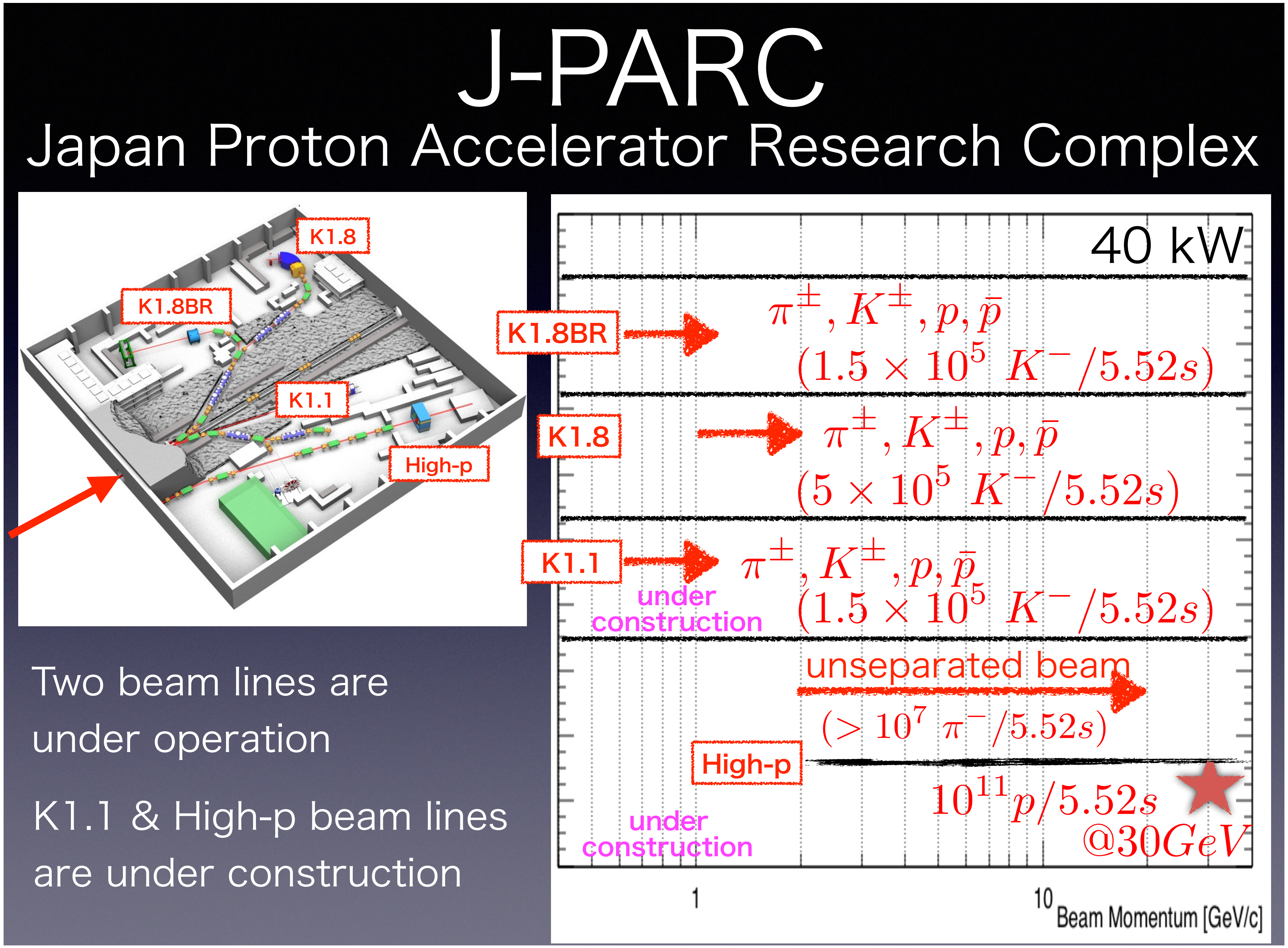
Tally #1: 3200 n/(s cm^2)
Tally #2: 40 n/(s cm^2)
Tally #3: 140 n/(s cm^2)
Tally #4: 3 n/(s cm^2)

Neutron Flux 10e+10/4*pi*/s



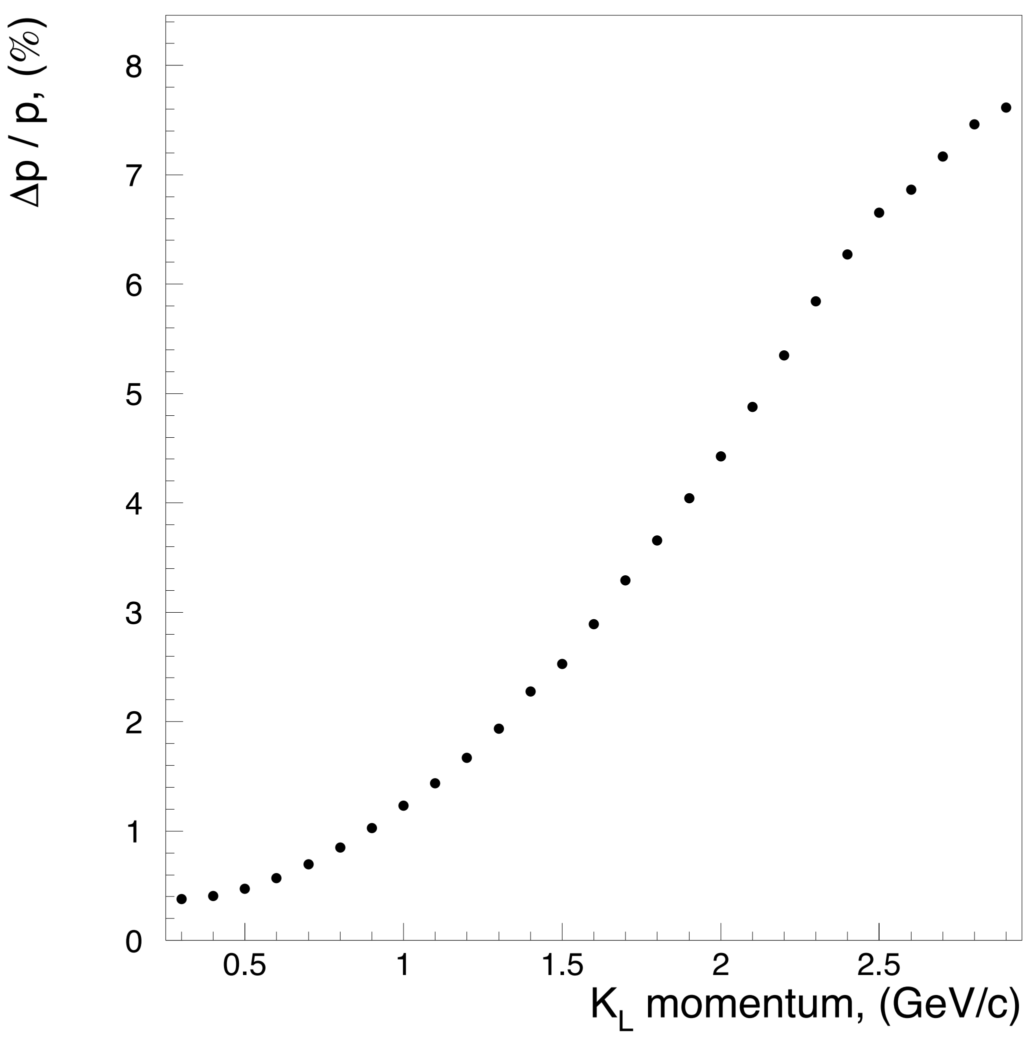
- **Conclusion: Neutron Flux in Hall D is tolerable**

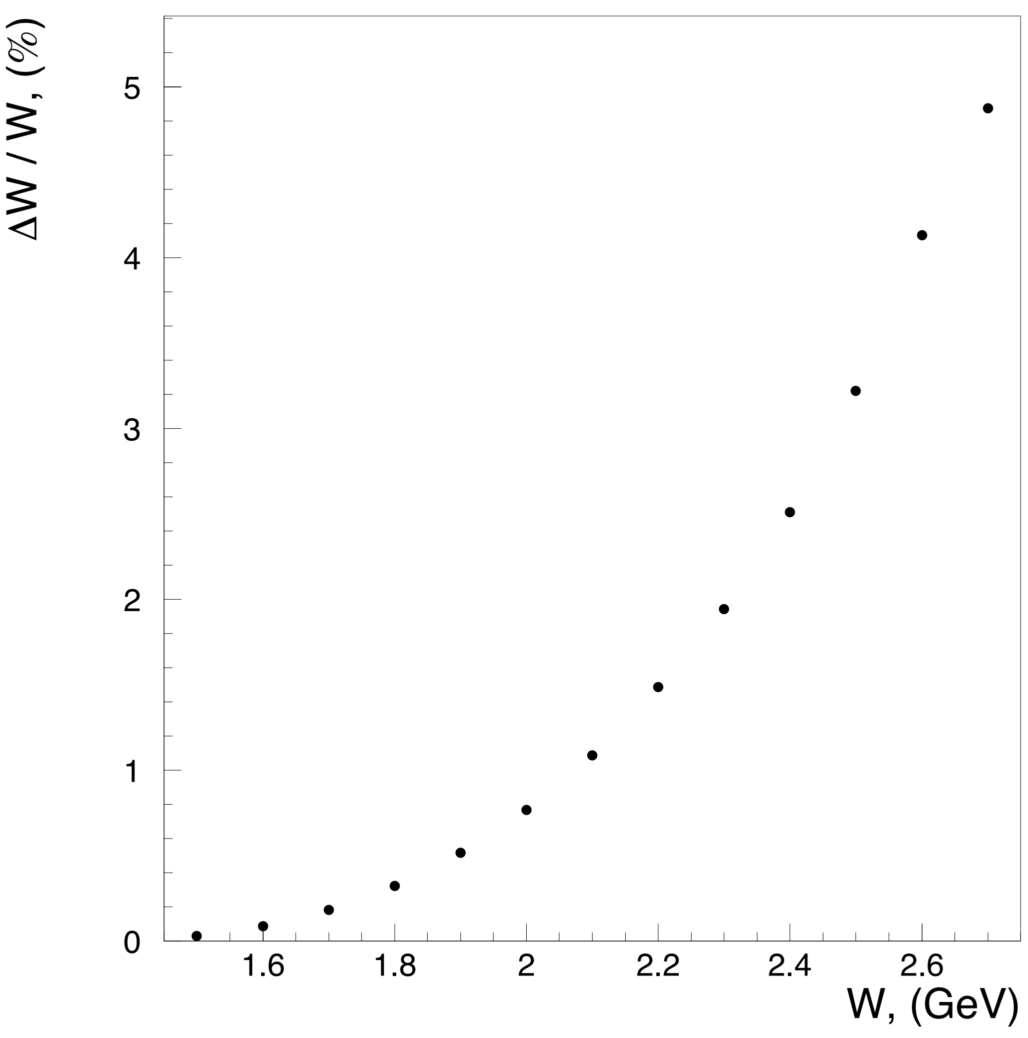
Other Facilities



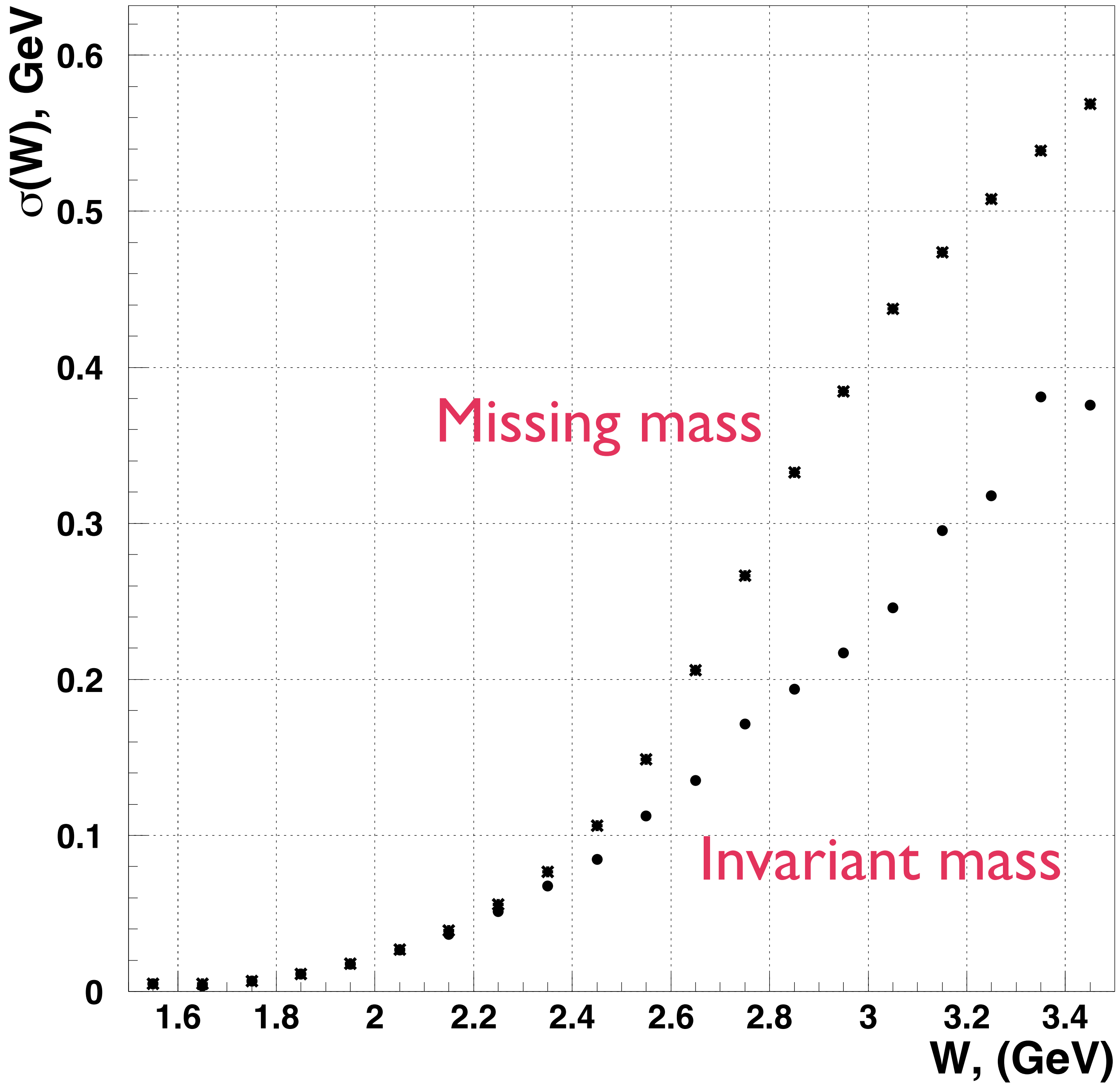
Talk by Onishi at KL2016

Momentum and W Resolution

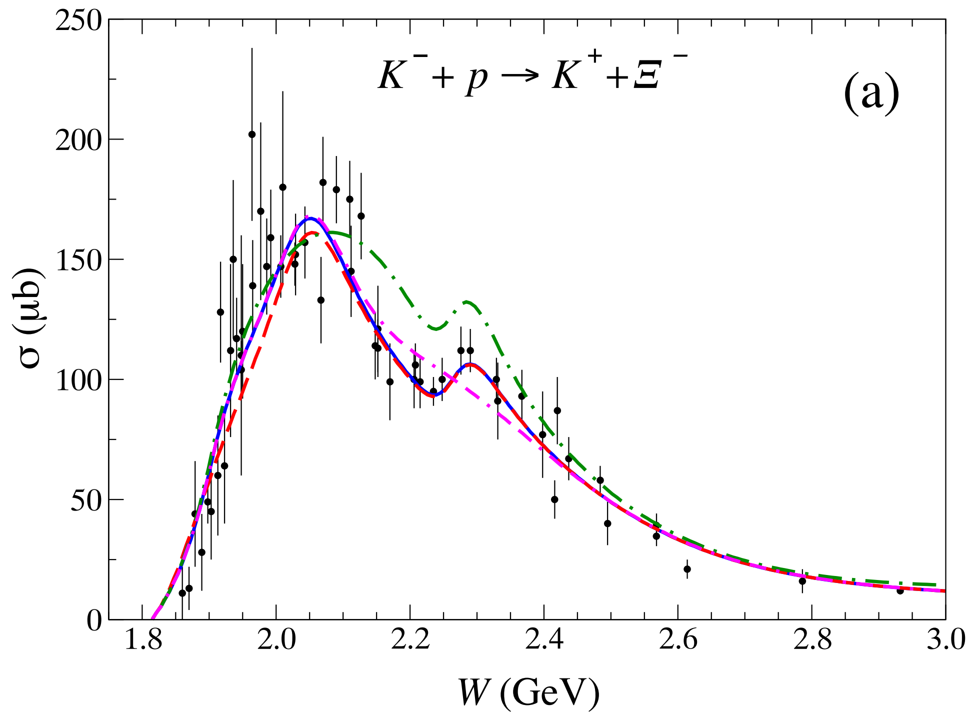


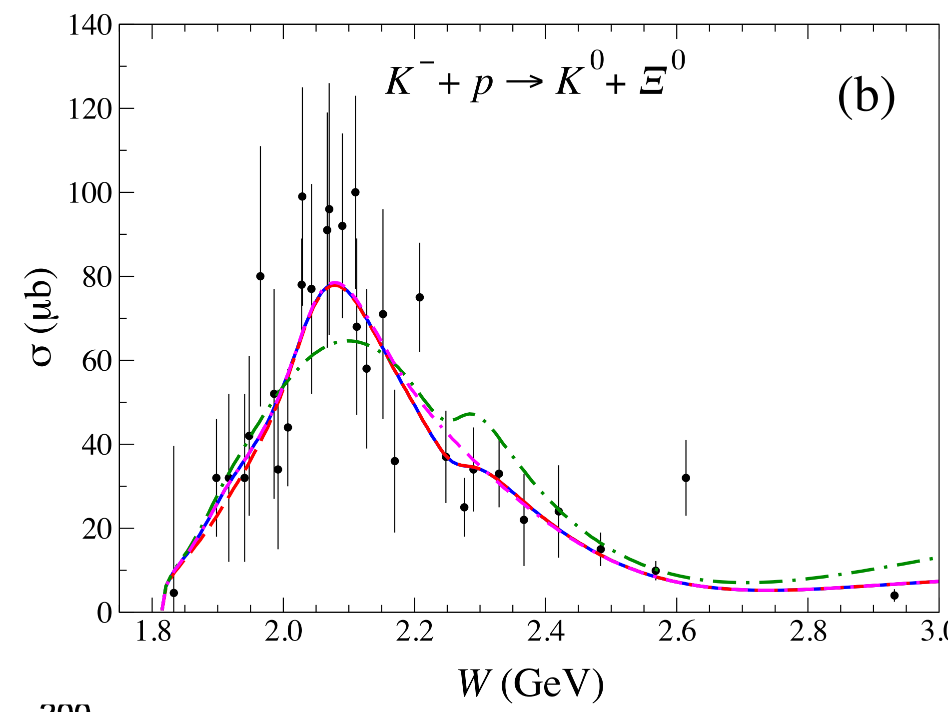


W-Resolution

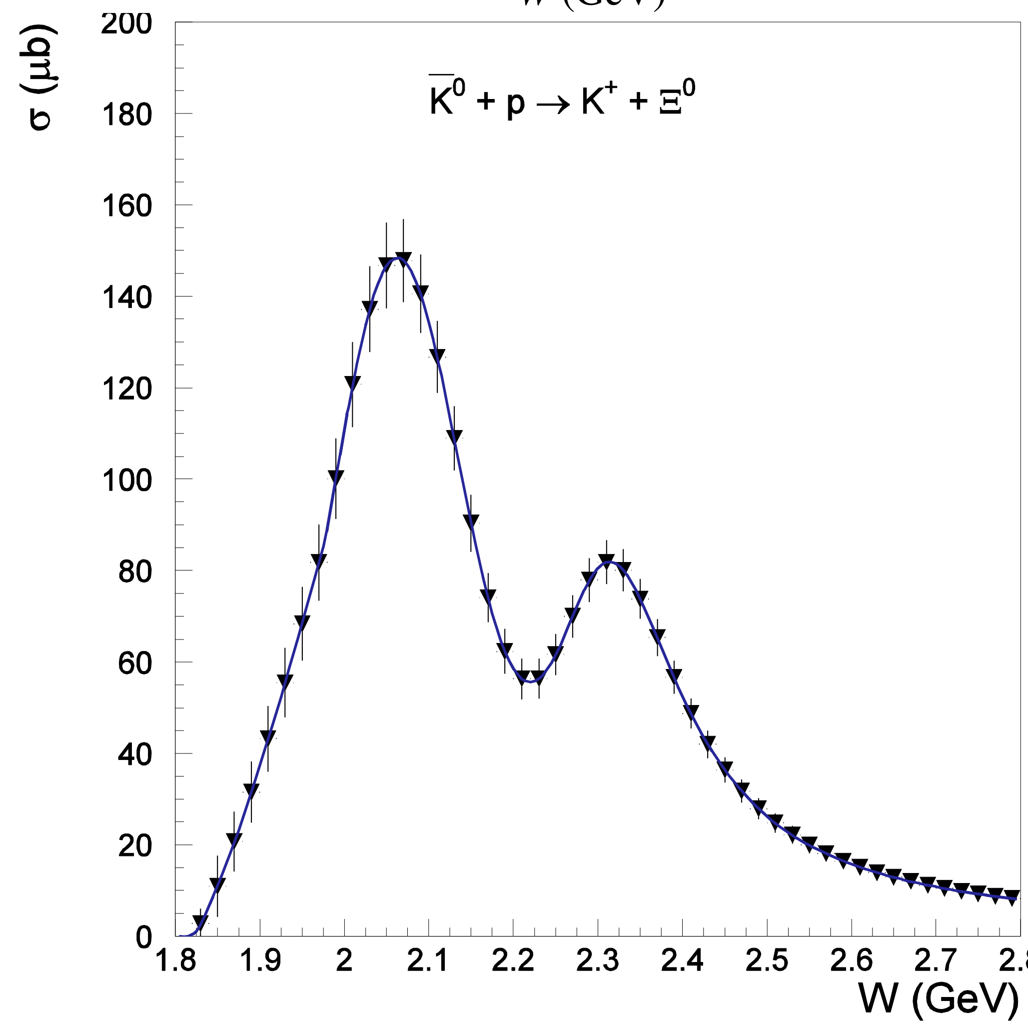


World Data on Ξ





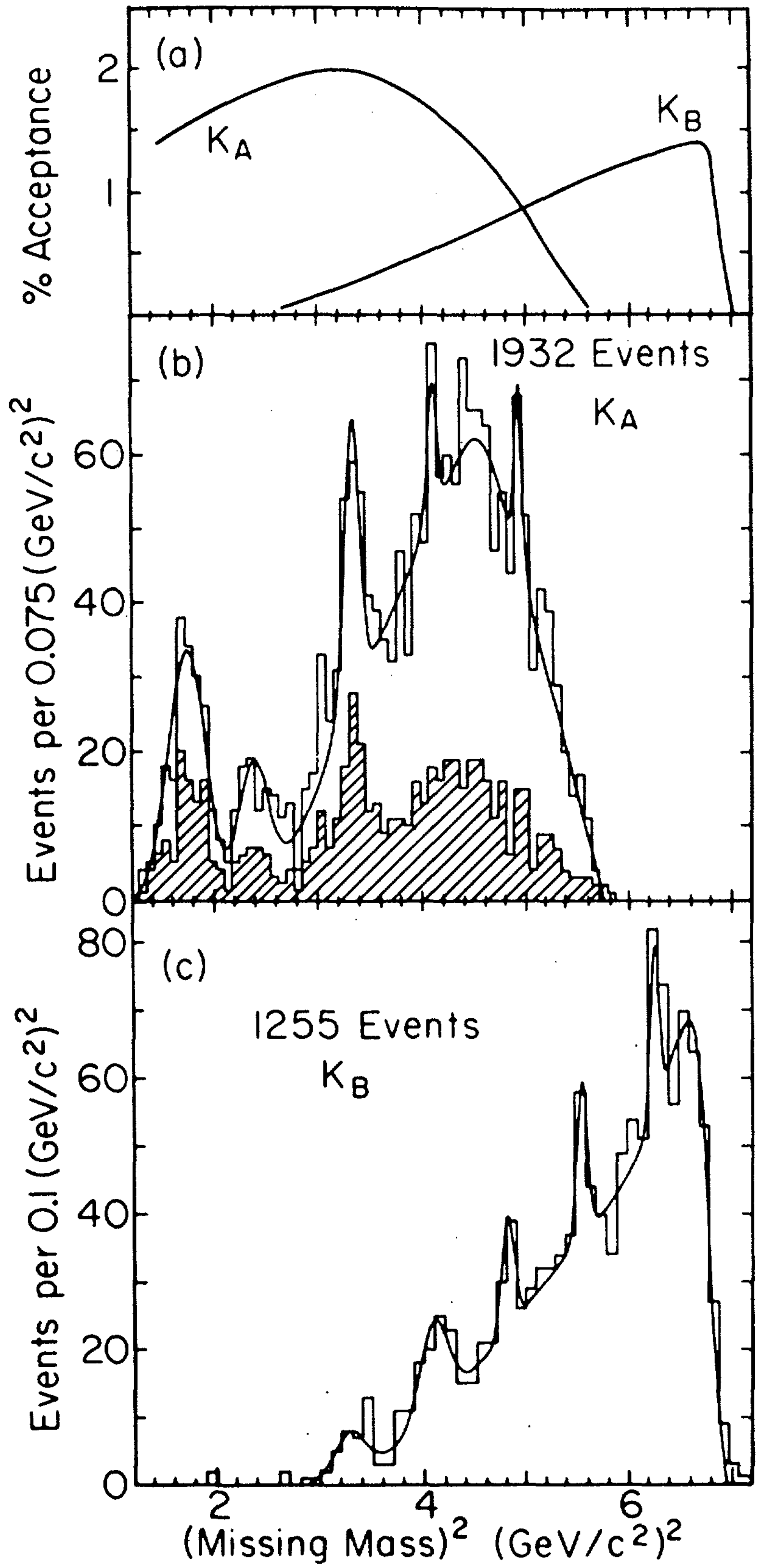
Simulated with GlueX
10^4 K_L/sec, one day of running



Jackson, Oh, Haberzettl, Nakayama
Phys. Rev. C 91, 065208 (2015)

Status of Ξ^*

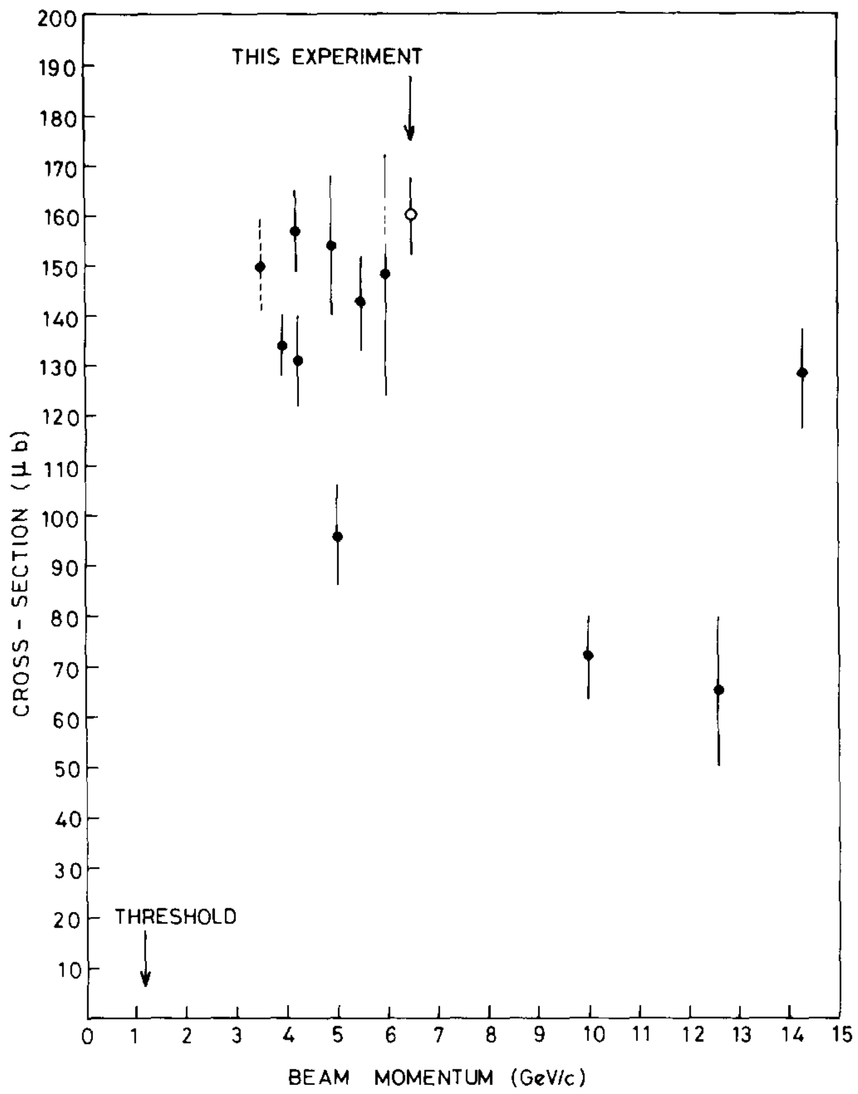
Very poorly measured at AGS (BNL) 32 years ago



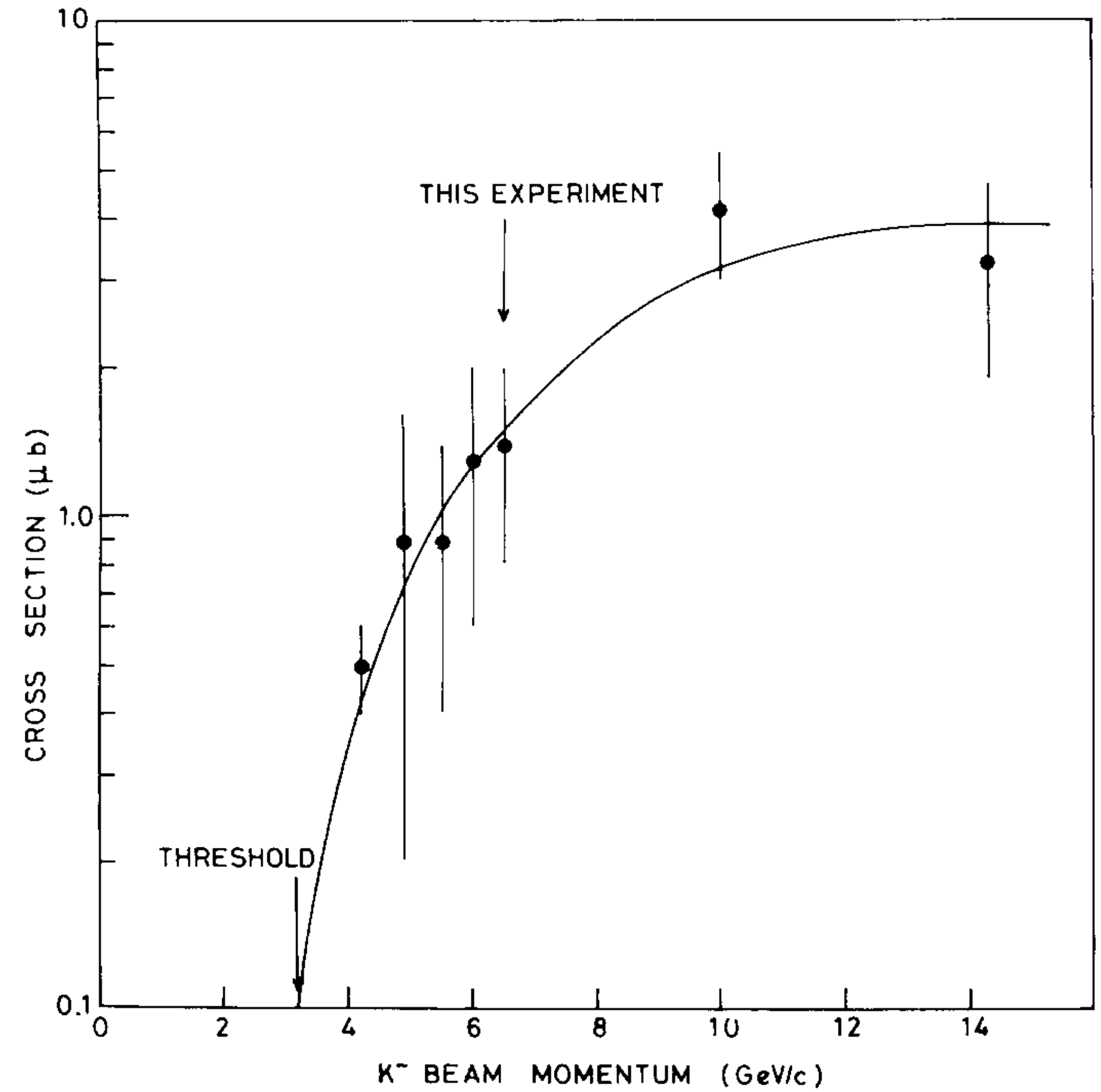
. C.M. Jenkins et al., Phys. Rev. Lett. 51, 951 (1983)

Cross Sections

$$K^- p \to \Xi^- X$$



$$K^- p \to \Omega^- X$$



J.K. Hassal et al., NPB 189 (1981)

Expected rates

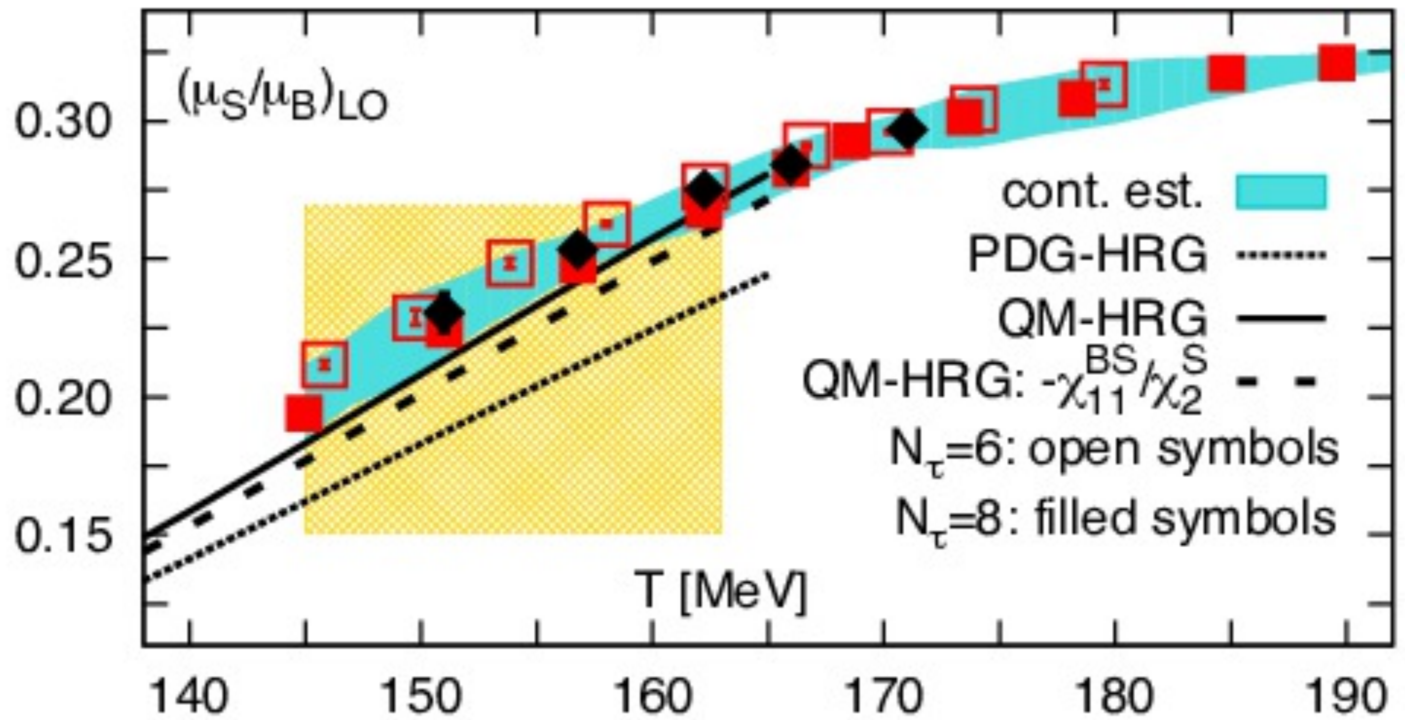
Production	J-PARC*	Jlab (this proposal)
flux/s	$3 \times 10^4 K^-$	$10^4 K_L^0$
$\Xi^* / month$	3×10^5	2×10^5
$\Omega^{-*} / month$	600	4000

* H.~Takahashi, NP A 914, 553 (2013)
M.~Naruki and K.~Shirotori, LOI-2014-JPARC

Missing states and freezout in heavy ion collisions

Close to T_c relaxation rates become small compared to the expansion rates and the system created in heavy ion collisions freezes out
The freeze-out is characterized by: (T^f, μ^f_B, μ^f_S) and hadron abundancies can be calculated from HRG

Lattice QCD Calculations



$$dU = TdS - PdV + \sum_{i=1}^{n} \mu_i dN_i$$

Bazavov et al., PRL 113(2014) 072001

chemical potential $\mu_i = \frac{\partial U_i}{\partial N_i}$

see also YSTAR2016 Workshop mini-proceedings arXiv:1701.07346

12 GeV Approved Experiments by PAC Days

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD		119		540		**659**
The transverse structure of the hadrons	145.5	85	102	25		**357.5**
The longitudinal structure of the hadrons	65	230	165			**460**
The 3D structure of the hadrons	409	872	212			**1493**
Hadrons and cold nuclear matter	180	175	201		14	**570**
Low-energy tests of the Standard Model and Fundamental Symmetries	547	180		79	60	**866**
Total Days	**1346.5**	**1661**	**680**	**644**	**74**	**4405.5**
Total Days – Without MIE Days	**697.5**	**1661**	**680**	**644**	**28**	**3710.5**
Total Approved Run Group Days (includes MIE)	**1346.5**	**826**	**637**	**424**	**74**	**3307.5**
Total Approved Run Group Days (without MIE)	**528.5**	**826**	**637**	**424**	**28**	**2443.5**
Total Days Completed	**20**	**15**	**0**	**25**	**0**	**60**
Total Days Remaining	**508.5**	**811**	**637**	**399**	**28**	**2383.5**

60 weeks

U.S. DEPARTMENT OF ENERGY | Office of Science | JSA   June 2016   11   Jefferson Lab

- **Bob McKeown's talk at 2016 UG meeting**

JLab Operations Budget ONP Briefing

- During FY01-FY12, CEBAF ops averaged 34.5 weeks/year (best year FY05 at 42 weeks)

- For 12 GeV era we estimate "optimal" operations at 37 weeks per year

- FY17 Pres. Budget includes JLab ops at $104M
  - would fund 23 weeks (+ 3 weeks from 12 GeV project)

- FY18+ at cost of living implies 23 weeks/year running (62% of optimal)

- We propose FY18+ at 30 weeks/year (81%), will require ~$6M increase in operations budget.

- **Slide from Mont's talk at 2016 UG meeting**
- **Hall D Physics Program will be completed in 2-3 years**

Summary

- KN scattering still remains very poorly studied

- lack of data on excited hyperon states requires significant experimental efforts to be completed

- Our preliminary studies show that production of few times$10^4 K^0_L$/s at GlueX target in Hall D is

-Proposed setup will have highest intensity K^0_L beam ever used for hadron spectroscopy
two orders of magnitude higher than in LASS (SLAC) experiment

-Data obtained at Jlab will be unique and partially complementary to charged kaon data

-The possibility to run with polarized H and D targets is possible (see talk by C. Keith at KL2016 Workshop)

Thank You!